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SEPTEMBER 1954

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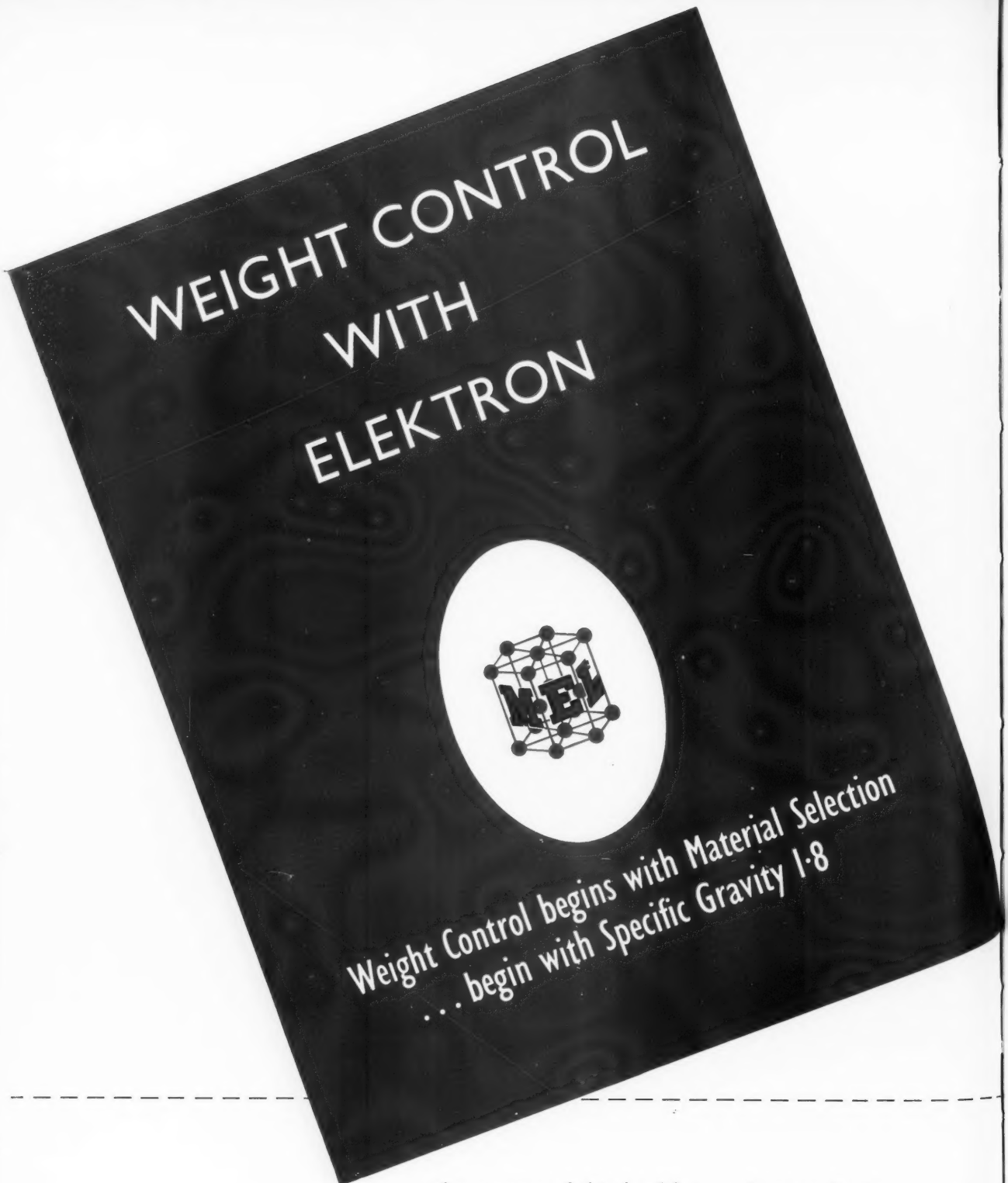

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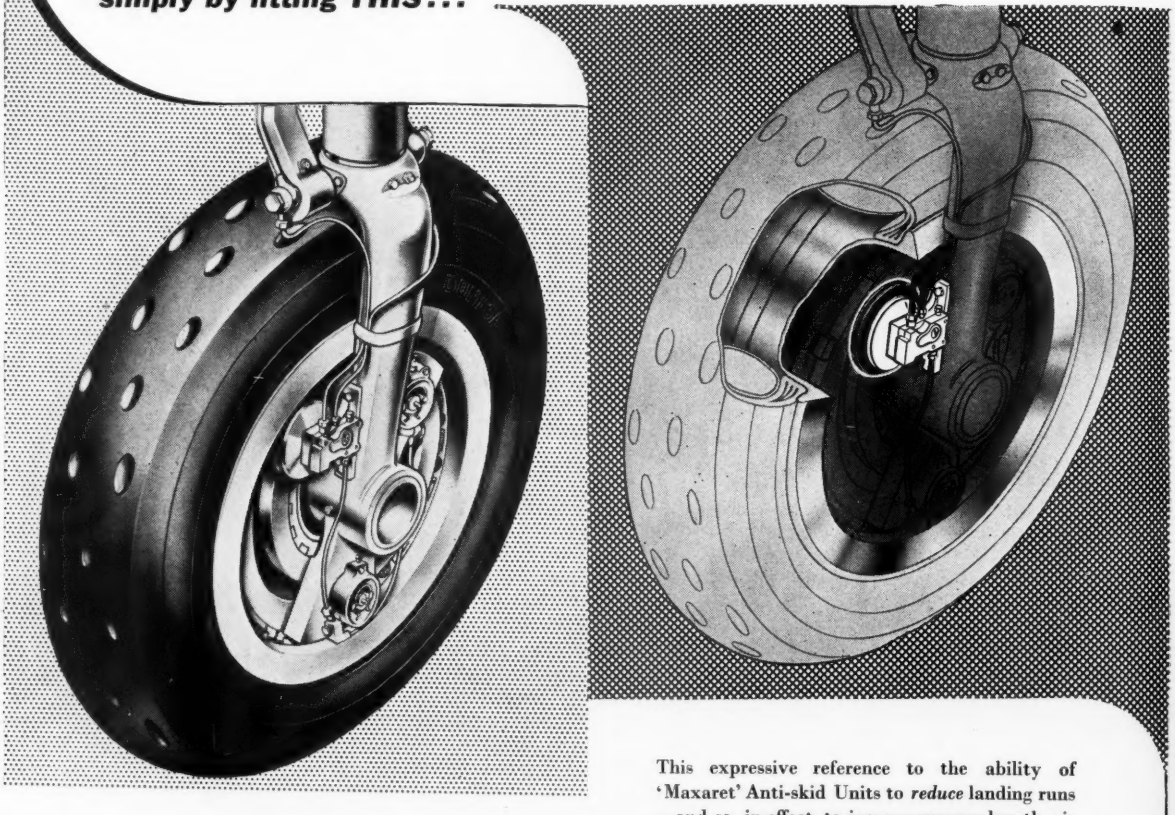

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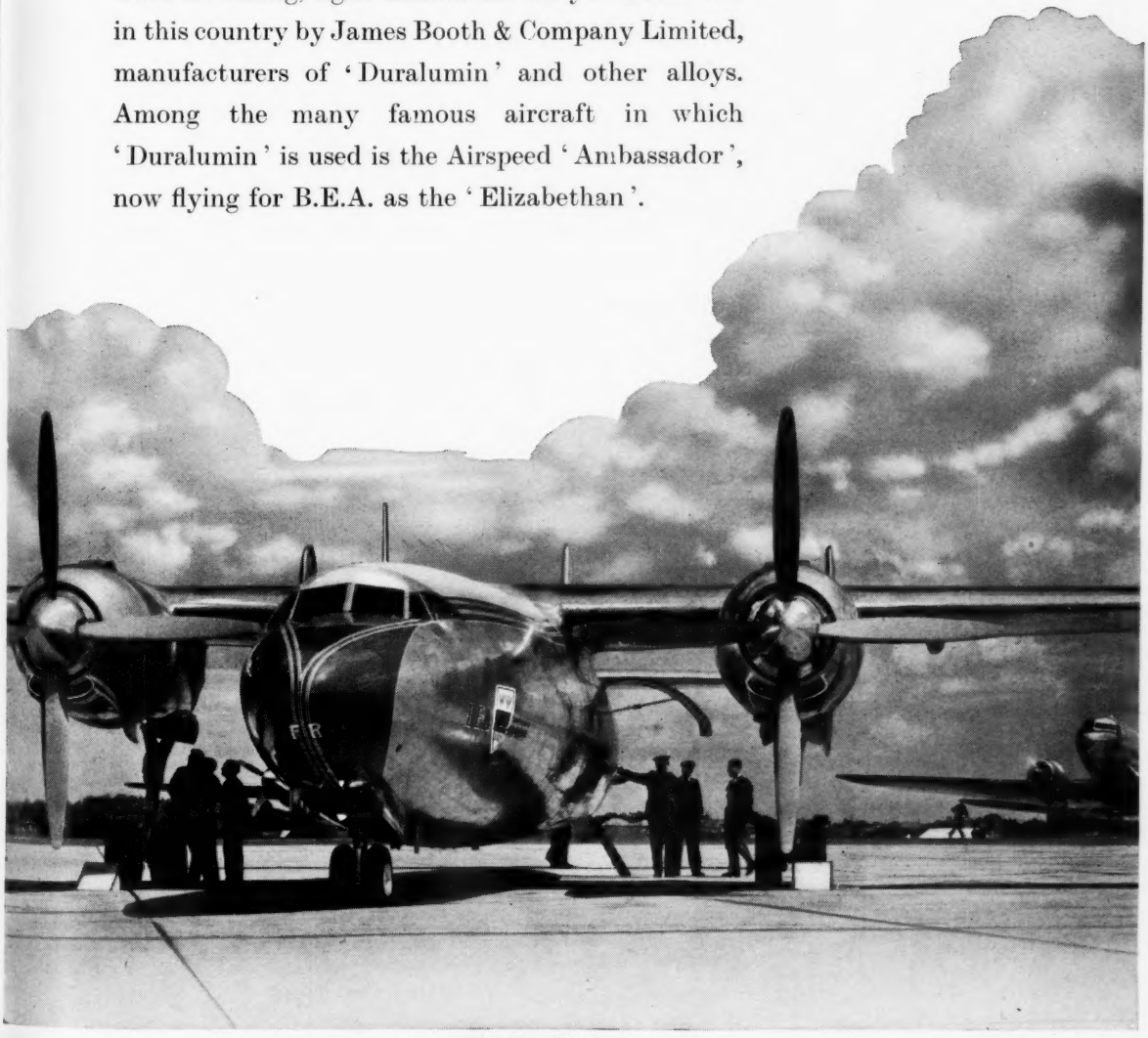

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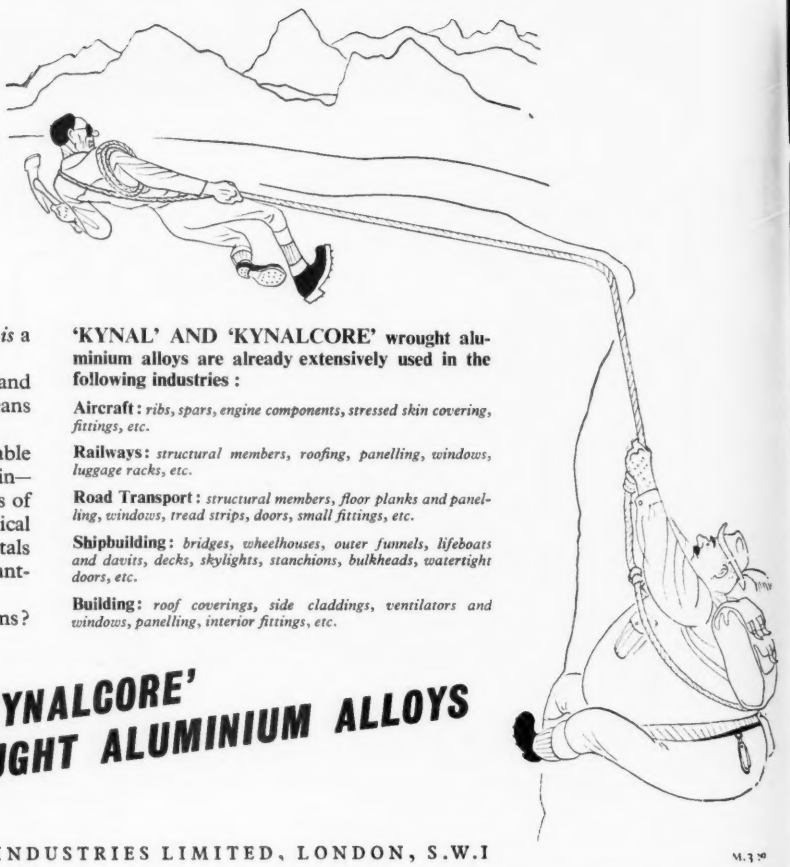

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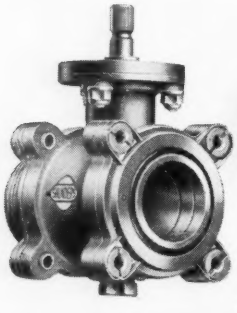

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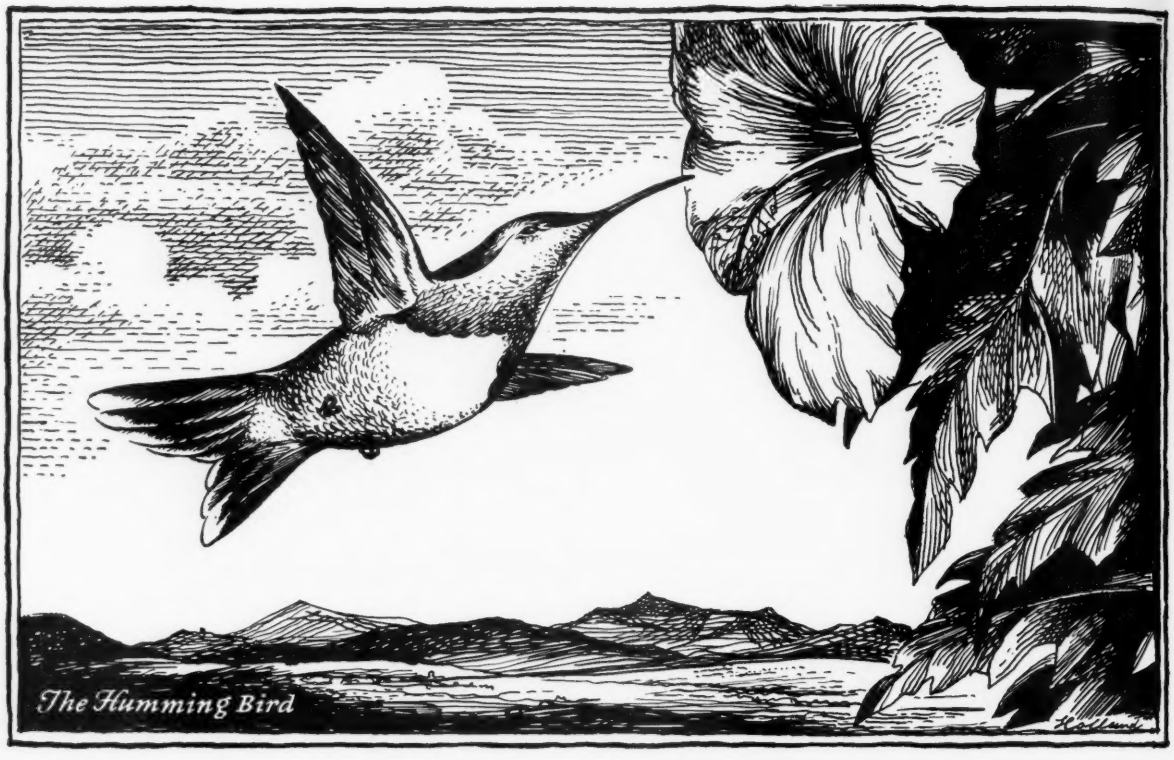
Problems of flight

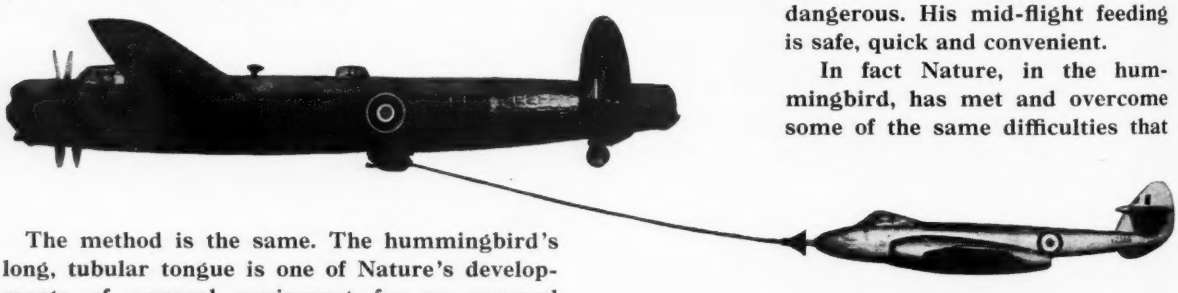


REFUELLING IN FLIGHT

Refuelling in flight is as old as the earliest hummingbird. Nature devised it as a special solution to special problems. Now man, faced by the same problems, has thought of it too.

Though he flies so swiftly that you can see only a blur of brilliant colour—though, unique among birds, he can fly backwards—he is vulnerable to a thousand watchful enemies. Landing could be dangerous. His mid-flight feeding is safe, quick and convenient.

In fact Nature, in the hummingbird, has met and overcome some of the same difficulties that man—who knows how many thousand years later—has met and overcome in short-range fighter aircraft.



The method is the same. The hummingbird's long, tubular tongue is one of Nature's developments of unusual equipment for an unusual purpose. The bird uses it by hovering over a flower, manœuvring until his beak is in position to plumb the heart of the blossom, and then syphoning up the nectar.

There is good reason for this astonishing technique. The hummingbird is tiny. (With his gaudy colouring and his wings beating invisibly fast he looks more like an insect than a bird.)

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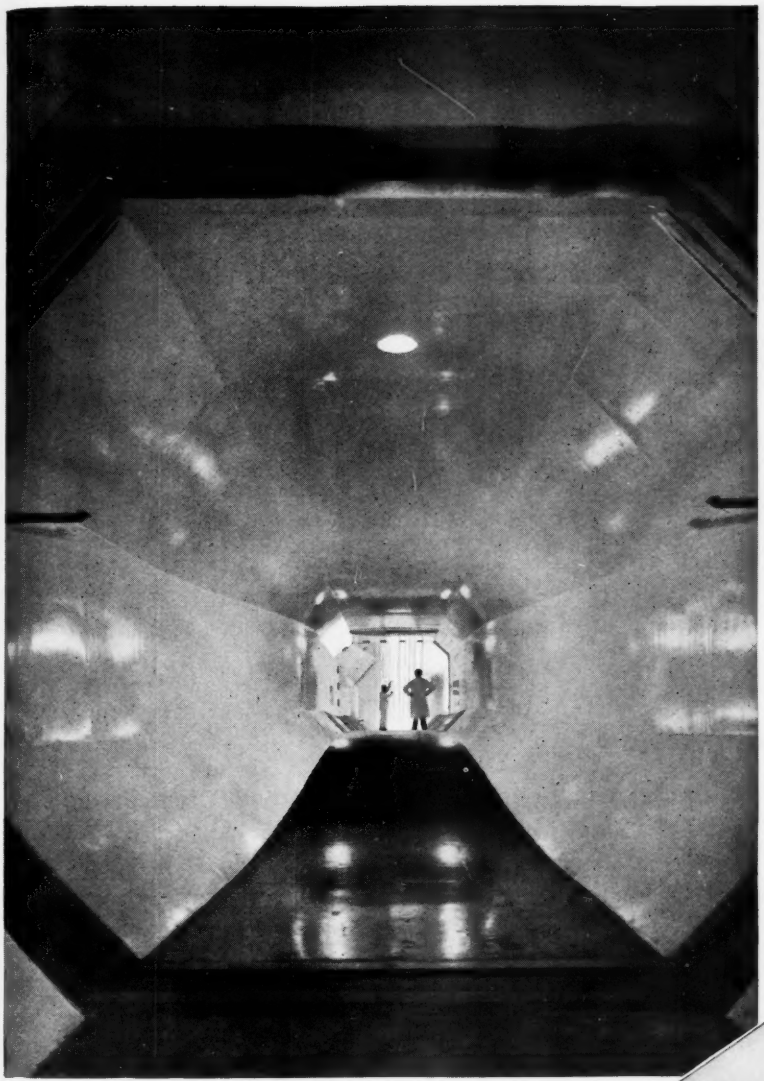

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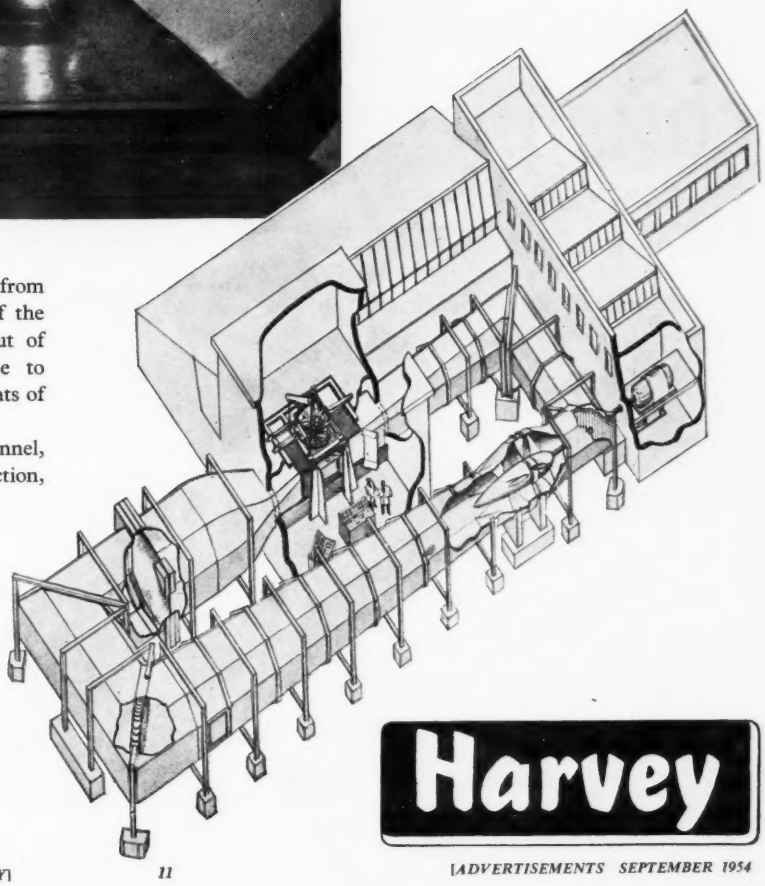

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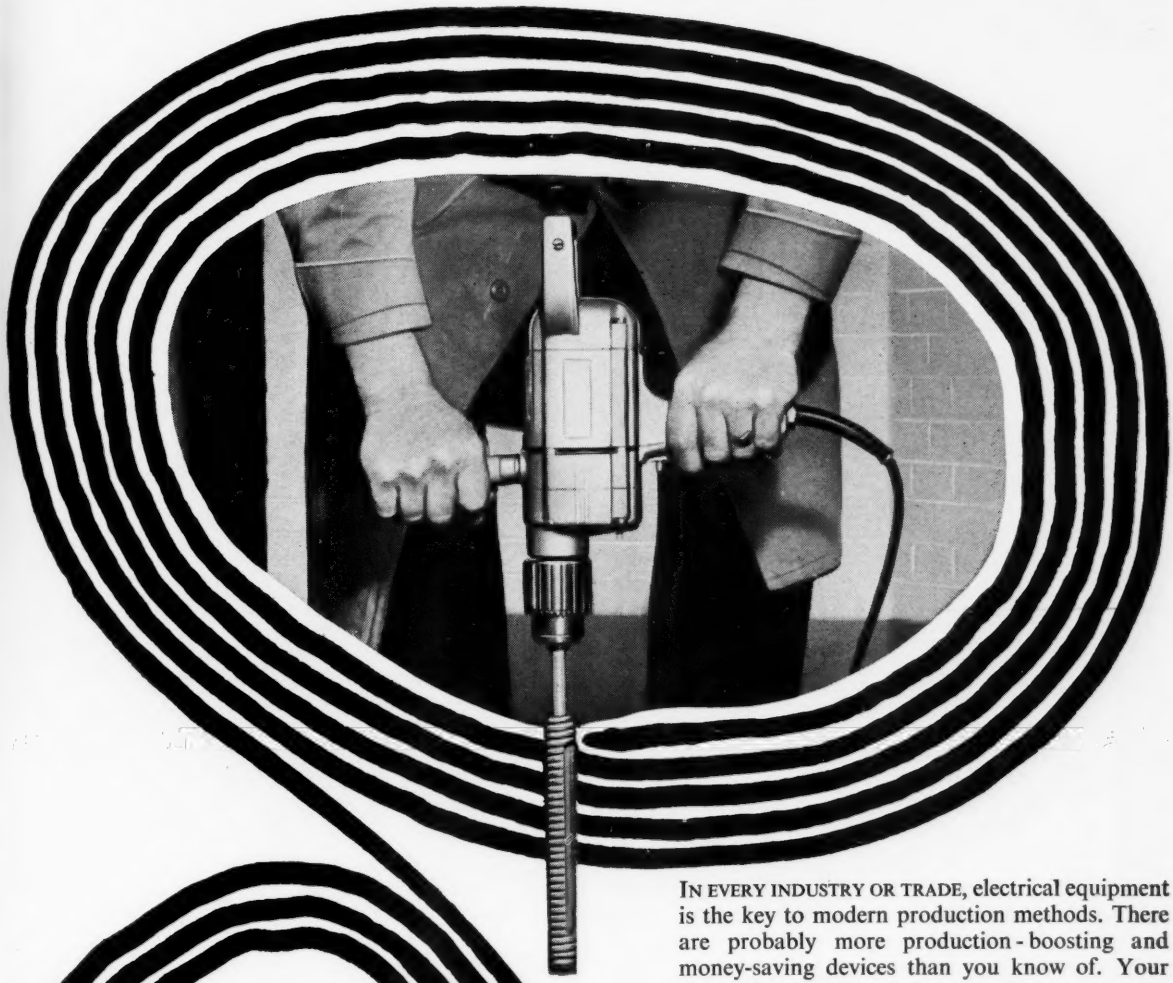

Drilling for—Rag Bolts!

It sounds strange. But most of us have seen a rag bolt even if we haven't recognised it. Machinery on a concrete floor, bolted down. The bolts embedded in the concrete are rag bolts. In the old days it was a case of a man with hammer and chisel—laboriously and slowly chipping the concrete until the holes were large enough and deep enough. Now one man takes an electric drill, and drills *the holes; just like that. (Productivity!) Faster? Fifty times—a hundred! But the electric drill is ONLY ONE OF THE MANY AIDS TO PRODUCTIVITY THAT ELECTRICITY CAN BRING YOU.*

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BESNIER'S MACHINERY

IN 1678, in the French town of Sable, a locksmith named Besnier, tired of anticipating Yale, equipped himself with wings, and jumped off a stool. *Le Journal des Savants* of the period, which published the report, gives no hint of the met conditions at the time, but Besnier seems to have touched down successfully, for we next hear of him jumping off a table. Encouraged by these adventures, and by a flight through a moderately high window, the intrepid craftsman went upstairs and leaped out of the attic, "whence he flew over the neighbouring houses". The journal adds that Besnier didn't claim to stay in the air very long—and it will be seen that even for short flights he had to tie his hat on. He affirmed, however, that taking off from a moderately elevated point, he could easily fly over a river of considerable breadth.

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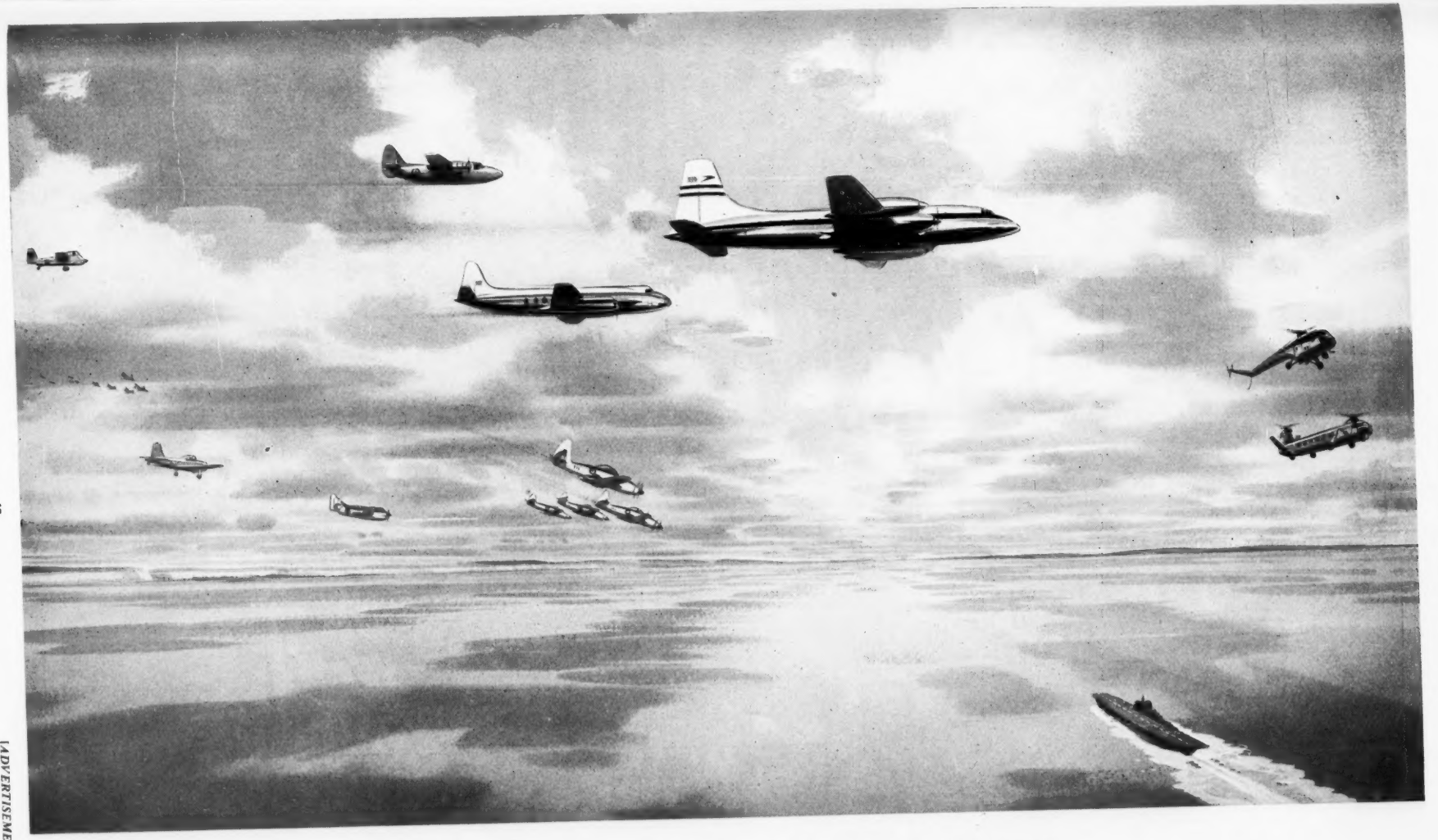

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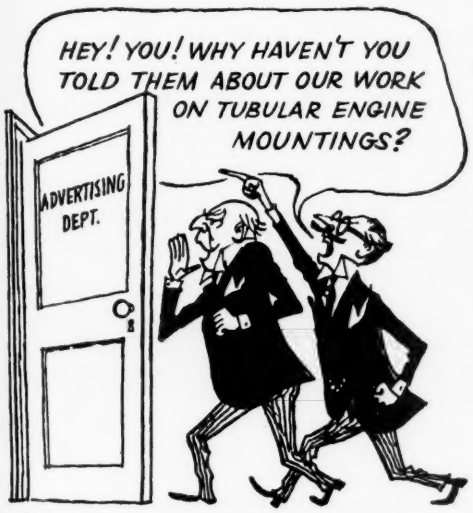

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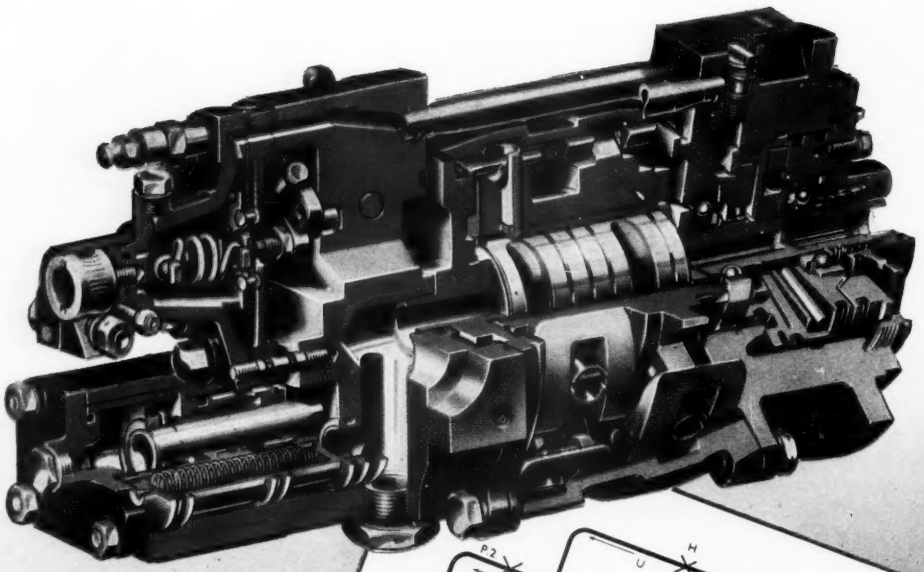

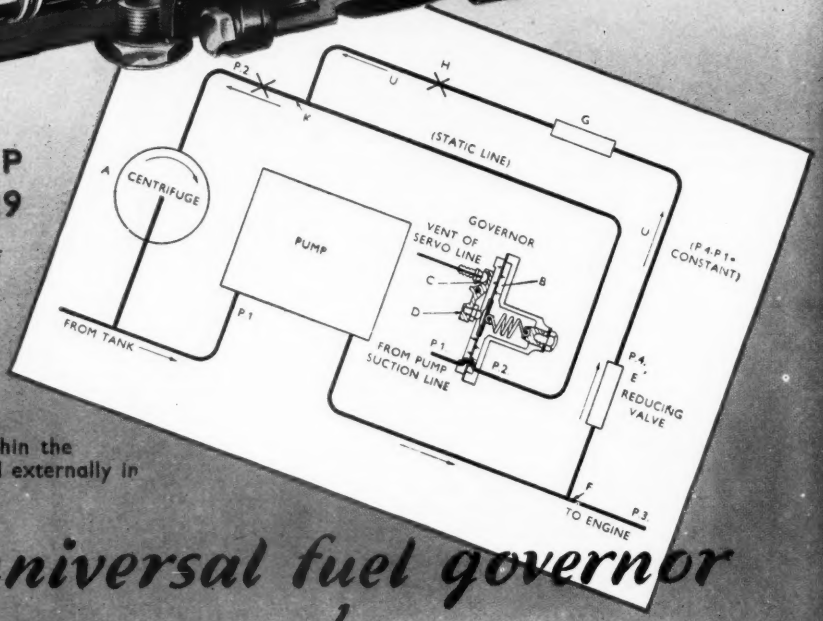

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NOTICES

An annual sum of £250 is available for premium awards for papers, including Technical Notes, published in the Journal. Members and non-members of the Society are invited to submit papers on any aspect of aeronautics

Fifth Anglo-American Conference

The Fifth Anglo-American Aeronautical Conference will be held in Los Angeles, California, from 20th June to 1st July 1955. Detailed plans for the lectures and visits are now being made and are nearly complete. An application form for membership of the Conference, giving details of the travel and hotel arrangements, will be included in the October Journal.

The British Lecturers will be:—

Mr. S. D. Davies, A. V. Roe; Dr. D. W. Holder, National Physical Laboratory; Mr. C. F. Joy, Handley Page; Mr. A. A. Lombard, Rolls-Royce; Mr. P. G. Masefield, British European Airways; Mr. R. J. Monaghan, Royal Aircraft Establishment; Dr. E. S. Moult, de Havilland Engine Company; and Dr. P. B. Walker, Royal Aircraft Establishment.

Visits and Social functions are being planned in the Los Angeles, San Diego and San Francisco areas.

Model Aerodynamics Conference

The Low Speed Aerodynamics Research Association will hold an All-day Conference on Model Aerodynamics on 25th September at 4 Hamilton Place from 10 a.m. to 5 p.m. Further details may be obtained from Mr. T. Dorricott, 84 Marston Gardens, Luton.

Library

The Library will be closed on Saturday morning, 25th September 1954.

News of Members

Commander E. H. Banfield (*Associate Fellow*) has left his appointment as the Air Engineer Officer at the R.N. Air Station, Lossiemouth, and has been re-appointed as Yard Manager and Deputy Superintendent at the Royal Naval Aircraft Yard at Donibristle, Fife.

A. D. Barber (*Graduate*) has been awarded a King George VI Memorial Fellowship tenable at Columbia University, U.S.A.

Commander F. W. N. Bassett, R.N. (Retd.) (*Associate Fellow*), formerly Director and Commercial Manager of Normalair Ltd., has been appointed Commercial Director.

W. G. Carter, C.B.E. (*Fellow*) has retired from his post of Technical Director, Gloster Aircraft Co. Ltd., but is to remain available to the Company in a consulting capacity.

F. T. Hearle (*Fellow*) has relinquished his position as chairman of the de Havilland Aircraft Co. Ltd. on medical advice.

Dr. W. F. Hilton (*Fellow*) has received from the Senate of the University of London the degree of Doctor of Science for his work in the field of aerodynamics.

C. F. Uwins (*Fellow*), who was recently elected Vice-President of the Society of British Aircraft Constructors, has been nominated by the Bristol Aeroplane Co. to serve on the Board of Short Bros. and Harland Ltd.

R. W. Walker (*Fellow*), Chief Designer, Gloster Aircraft Co. Ltd., has been appointed to the Board of the Company.

G. W. M. Williamson (*Associate Fellow*) has taken up an appointment as an Engineer with the Ministry of Supply at Chessington.

P. W. Wreford-Bush (*Associate Fellow*) has now become Group Leader in charge of the Engineering Experimental Flight Test Group at Canadair Ltd.

Diary

LONDON

September 30th
Graduates' and Students' Section. Air-to-Air Photography. Russell Adams. 4 Hamilton Place, W.1. 7.30 p.m.

October 12th
Section Lecture. Behaviour of Light Alloys at Elevated Temperatures. B. C. Gadd. 4 Hamilton Place, W.1. 7 p.m.

October 19th
Graduates' and Students' Section. The Propeller-Turbine in Airline Service. T. M. Corson. 4 Hamilton Place, W.1. 7.30 p.m.

October 21st
Main Lecture. The Development of Re-Heat. J. L. Edwards. At the Institution of Mechanical Engineers, Storey's Gate, S.W.1. 6 p.m. (Tea 5.30 p.m.)

BRANCHES

September 6th
Halton. Films. Wings for the World and Racing Films. Branch Hut, R.A.F. Station, Halton. 6.45 p.m.

September 13th
Halton. Birds on the Beam. Dr. Matthews. Branch Hut, R.A.F. Station, Halton. 6.45 p.m.

September 15th
Coventry. New Developments in Aircraft Production Engineering. Professor J. V. Connolly. Wine Lodge, Coventry. 7.30 p.m.

September 20th
Halton. Branch Night. Branch Hut, R.A.F. Station, Halton. 6.45 p.m.

September 27th
Halton. General Meeting of Junior Members followed by films. Branch Hut, R.A.F. Station, Halton. 6.45 p.m.

October 2nd
Halton. Annual General Meeting followed by tea; 4 p.m. Lecture 6.30 p.m. Branch Hut, R.A.F. Station, Halton.

October 4th
Glasgow. Practical Experience of Airline Engineering. R. C. Morgan. Royal Technical College. 7.30 p.m.

October 11th
Halton. Pilot Training for the R.A.F. Technical Branch. Squadron Leader H. G. A. Scilley. Branch Hut, R.A.F. Station, Halton. 6.45 p.m.

Graduates' and Students' Visits

A water tour from Charing Cross Pier to view the London Docks has been arranged from 6.00 to 9.00 p.m. on Saturday, 18th September, at a fare of 4/- per head. Meals will be available, and the vessel is fully licensed. Members and friends wishing to attend should apply immediately to the Honorary Visits' Secretary, P. D. Stewart, 217 High Road, East Finchley, N.2.

A visit has been arranged to the Royal Aircraft Establishment for Wednesday 13th October 1954 at 10.30 a.m. Lunch will be available. Visitors will be able to see the wind tunnel, structural and engine test rigs and the flight test department.

The numbers for this visit are strictly limited and applications should be sent not later than 6th October to the Honorary Visits Secretary, P. D. Stewart, 217 High Road, East Finchley, N.2. Applicants are asked to state their grade of membership of the Society and that they are British subjects.

The Aeronautical Quarterly

Part 2, Volume V of the Aeronautical Quarterly (July 1954) is now available from the Offices of the Society at 7s. 9d. per copy to members or 15s. 3d. to non-members, including postage and packing.

The contents of Part 2, Volume V are:—

The Compressible Laminar Boundary Layer on a Yawed Infinite Wing	*L. F. Crabtree*
The Natural Frequency of Vibration of Curved Rectangular Plates	*P. J. Palmer*
A Note on the Supersonic Downwash Integral	*B. A. Hunn*
The Design of Thin Finite Wings in Incompressible Flow	*G. J. Hancock*
Symmetrical Buckling of Right-Angled Isosceles Triangular Plates	*W. H. Wittrick*
Subsonic Compressible Flow Past Bluff Bodies	*A. L. Longhorn*

The cost of subscriptions to Volume V for non-members has been increased to £3 1s. 0d. including postage and packing. There has been no increase for members.

Copies of all issues of The Quarterly are still available and subscriptions for all Volumes can still be accepted. Prices for Volumes I-IV, including postage and packing, are: *Members*—per part 7s. 9d. Subscriptions (4 parts) £1 11s. 0d. *Non-Members*—per part 10s. 3d. Subscriptions £2 1s. 0d.

Journal Binding

Self-Binder Cases

Self-Binder cases of the "Easibind" type are available from the offices of the Society. These binders are for members who do not have their Journals permanently bound, or who wish to keep their Journals together during the year for binding later.

These cases will hold 12 Journals which are kept in place by means of flexible steel wires. Journals can be inserted or withdrawn easily without damage, so preserving the contents for permanent binding later. The Journals will open flat at any page.

The binder is strongly made in durable dark blue leather cloth on stiff board covers and has gold lettering on the spine. The year is not blocked on the spine but there is a panel on which members who wish to use the binder as a permanent case can put the date.

The cost is 11s. 6d. each including postage and packing for either the size to fit 1952 and previous Journals, or for the size to fit the Journal from January 1953, which has been increased in size. Orders and remittances should be sent direct to the Secretary at the Offices of the Society and it is *important to state whether the old size or new size is required.*

Permanent Binding

There is no increase in the price of permanent binding of Journals. The prices are:—

1953 Volume (including packing and postage) 16s. 0d.
Previous Volumes (including packing and postage) 18s. 0d.

Journals, *with a note of the name and address of the sender,* should be sent direct to The Lewes Press, Friars Walk, Lewes, Sussex, and the remittance to the Secretary at the Offices of the Society.

Elections

The following is a list of new members and transfers of membership of the Society:—

Associate Fellows

Frederick John Ballard (*from Associate*)
William Maurice Brady (*from Graduate*)
John Aubrey Brignell (*from Associate*)
Gordon Ronald Buxton
Francis Cumberland (*from Associate*)
Herbert Harrison Dent
Paul Kitchenside Digby (*from Graduate*)
Lewis Henry Wilson Harris (*from Graduate*)
Evelyn Michael Thomas Howell
John Henry (*from Graduate*)
Norman Nash (*from Graduate*)
Neville Raymond Lloyd Quinn
Sydney Kenneth Reeves (*from Associate*)
John Ronald Rice
John Herbert Stephens (*from Graduate*)
Dennis Clifford Stevenson (*from Graduate*)
Douglas Warner Williams (*from Associate*)
Peter James Windibank (*from Graduate*)

Associates

Robert Desmond Bowman Archer
Percy Geoffrey Ball (*from Graduate*)
Frederick Edward Etheridge
Raymond Alva Fry
Herbert Henry Martin Harmer
James Hodgkinson
Bertram Melvin Hubbard
John Victor Iorns
Nazuvingal Paul Lazarus
Douglas Edgar Sharpe
Howard Arthur Charles Thompson
Colin Oliver Turner

Graduates

James Ernest Cleaver (*from Student*)
Jose Manuel de Sendagorta
Donald Haydn Dykins
John Yeates Mann
Gregory Earle Masterson
Michael Cooper Neale
David Howard Perry
John David Roberts (*from Student*)
John Howard Sargeant
Ann Isobel Taylor
James Velkou (*from Student*)

Students

Donald Vincent Baker
Roy Murray Braybrook
George Taylor Sutton Done
Michael John Evans
Frank William Light
Edward Thomas Osborne
Narendra Parshu Ram

Companions

Kenneth Samuel Nice
Neil Thompson Scott

Changes of Address

To assist in keeping the records of members correct and up to date the Secretary will be glad if all members will notify him as soon as possible of changes of address.

When notifying changes please give the following particulars:—

Name (in block letters). New address (in block letters).
Grade of Membership. Old address.

Changes of address must be received *before the 15th of the month* in order to be effective for the Journal for the following month.

The Journal of the Royal Aeronautical Society

WITH WHICH IS INCORPORATED THE INSTITUTION OF AERONAUTICAL ENGINEERS

VOLUME 58 SEPTEMBER 1954 NUMBER 525

Practical Experience of Airline Engineering

by

R. C. MORGAN, O.B.E., F.R.Ae.S.

(Chief Project and Development Engineer, British European Airways)

The 909th Lecture to be given before the Society and the 16th Main Lecture at a Branch, was held under the auspices of the Chester Branch of the Society on 8th April 1954. Mr. K. G. Hancock, Chairman of the Chester Branch, expressed the pleasure of the Branch at having a Main Meeting of the Society at Chester and welcomed the visitors, particularly the officers of the Main Society. He then asked the President, Sir William Farren, to preside for the rest of the Meeting.

SIR WILLIAM FARRREN said it was an equally great pleasure to him, both as President of the Society and as an individual, to be present and to take the Chair. In the Society they regarded the Branches as their great strength; not only their present strength but for the future, because it was in the Branches, where he believed discussion was informal, fast and furious, that young people found the courage to get up and say what they thought and felt, and that was what really brought life into the Society; in London they were apt to be a little more staid at times.

The Lecture that evening was one in a field in which he thought they did not have enough papers, considering the importance to their country of civil aviation. He had read the paper and found it most interesting and hoped they would have a lively Discussion. The Lecturer, Mr. R. C. Morgan, whom he had had the pleasure of knowing for a long time, had had an interesting career in aviation. He believed that Mr. Morgan was one of the few people who had had quite a lot of experience in both aircraft and aero engines, which must be useful in his present position. He thought he was right in saying that Mr. Morgan was associated with the early history of the first British jet-driven aeroplane. Since 1945, Mr. Morgan had been Chief Project and Development Engineer with British European Airways.

PART I—ENGINEERING IN THE AIRLINE

Introduction

Some eight years ago, work first began on building up the new airline to become known as British European Airways.

It was an herculean task which had to be faced. There was a sprinkling of older hands drawing experience from the smaller airlines and from B.O.A.C. and its predecessors Imperial Airways and British Airways, and with this nucleus the job was undertaken of getting together some 7,000 staff, supplying them with tools and equipment, and acquiring new aircraft and premises.

During the 1939-45 War the airlines in the U.S.A., with a background of continuity extending over many years, had been consolidating their position in the transport industry. Over this period they had built up a very substantial fund of knowledge and experience on such matters as standards and methods of maintenance and operation, high equipment utilisation, costs, equipment manufacture and design.

In this country, work had started on the design and manufacture of new transport aircraft and the Brabazon Committee had laid down a series of design specifications. If these aircraft were to meet American competition in the export market, the full co-operation of British operators would be essential right from the specification stage through to the development in service. Therein lay a part of the attraction of the development job in B.E.A.

Technically, the task offered wide scope for the exercise of courage and initiative. The war had completely stopped the development of British air transport which was getting on its feet (or its wings) in the late 1930's, and it meant that a new industry was being created. Moreover, the tremendous strides in aeronautical knowledge and experience taken during the war made it possible to visualise aircraft of much more advanced design, aircraft which would require the development of new methods and techniques. There was a danger, certainly, with no experience of continuity

to fall back on and with the general lack of stability, that difficulties would arise; this in fact proved to be the case, but there was the compensation of doing a pioneering job—an opportunity for trying out new approaches and ideas in both the technical and administrative fields. Naturally there have been some mistakes and many projects have taken longer to mature than was originally hoped, but in the process many lessons have been learnt and much experience gained.

An additional factor was introduced by the decision to make B.E.A. the subject of one of the recent social experiments—a decision which came shortly after the broad basis on which B.E.A. was to function had been laid down. It was as a nationalised industry, therefore, that the actual formation and subsequent growth of the airline took place, a fact which has had many and varied effects on the task of Engineering within the airline.

The task of starting the new airline involved fitting together this jigsaw in the shortest possible time, so that operations could begin and, at the same time, laying the plans for the subsequent ten years or so—plans on which the technical and economic success of the airline would so clearly depend.

During the few years since its formation, we in B.E.A. have evolved a pattern of airline engineering which, while broadly similar to that now adopted in most of the larger airlines of the world, is in some ways perhaps unique.

It is the purpose of this paper to discuss a few of the lessons learnt during the formation and growth of the technical side of the airline. Of successes there have been many, and in the face of the various factors which have influenced the task (some of them well known but outside the scope of this paper) the degree of success achieved is perhaps surprising.

When considering what has been done, and the premises and equipment with which it has been done, it is well to remember B.E.A's decision in the early days to buy British. In line with this decision B.E.A. introduced the Viking as a new aircraft, operated it successfully and is now retiring it from service; latterly two new British main line types have been accepted and are currently being introduced into service. B.E.A. has thus been the first operator of no less than three new types of aircraft so far.

This support of the British Industry and the export drive has provided both the airline and the manufacturers with a great fund of experience, but it has cost (and is still costing) the airline a good deal.

The Airline Engineer

With the need in air transport for emphasis on "development in service" has grown up a new engineering profession—that of the airline engineer.

The Wright brothers were the engineers; they built, experimented, flew, maintained, modified and built again on the basis of their experience.

Since that time the manufacturer and the user have become separated with the expansion of the aircraft manufacturing industry. In the earlier years the successful construction and sale of an aircraft was the completion of the job. Afterwards all that was required was a pilot to fly it and a mechanic to maintain it. The equipment was simple to fly (if sometimes hazardous!) and straightforward to maintain.

This same pattern obtained broadly for many years on civil and particularly military, aircraft until during the 1939-45 War the formidable problem arose of modification to meet changing requirements and to provide development in service. Even then, the general method adopted was the removal of equipment from service, or substantial modification as a separate job after the aircraft came off the production line.

Nowadays, the completion and sale of the transport aircraft is only part of the job. The new aircraft has then to be tried out in practice and modified while in service, as a result of experience, until it is capable of repetitive use day in and day out for periods exceeding ten years.

The once popular conception that an aircraft is designed, built and then sold off the shelf to an operator who simply has to fly it and maintain it no longer holds good. As Mr. B. S. Shenstone, Chief Engineer, B.E.A., said in his Anglo-American lecture[1], "The aeroplane is the thing . . . to be developed, extrapolated and finally scrapped."

Nowadays maintenance is but one field of the work of the engineer in all the larger airlines in the world.

As the equipment became more complicated and the demands upon it and those handling it—mechanics, pilots, traffic staff—became more stringent, the need for professional engineers on the airline became more evident. Although beginning in many places, such as with the specification for the Empire Flying Boats by Imperial Airways, the new concept of the professional airline engineer probably took its firmest hold with the work of American Airlines on the specifications for the DC-3 and its subsequent development in service.

Experience of the performance and usefulness of the civil transport equipment in service has now become, not as in so many military cases, the performance of one task with the utmost efficiency at one moment in time, but *the continuous execution of a complex task all day and every day to an acceptable standard of efficiency, with no possibility of a pause.*

The very high initial cost of the modern transport aircraft means it has to operate continuously at high annual utilisation for periods approaching ten years, before the initial capital cost can be paid off and during this time all kinds of technical aerodynamic and engineering problems arise. Furthermore, over such a period, development of the equipment for operational and commercial reasons is bound to be required.

On top, therefore, of daily routine maintenance of the equipment to a continuous acceptable standard, the engineer in the airline has to cover a very wide field, including:

(*i*) Collecting and interpreting the experience of all parts of the airline (maintenance, flight

operations, traffic, schedules planning and so on), on the equipment in use.

(*ii*) Solving all the technical problems arising with the equipment.

(*iii*) Assessing proposals to alter the equipment.

(*iv*) Initiating action arising from the above, both as regards development of the equipment itself and techniques for its maintenance and operation.

(*v*) Interpreting the whole of this work into requirements for new equipment.

The only justification for the use of professional engineers on this sort of work within an operating organisation is that it should pay. It does pay, handsomely, since the engineer's entire energies are directed towards the two basic elements of success—safety and economy.

In relation to this problem of economy, it is interesting to note the recent remarks[2] by the Director-General of I.A.T.A., Sir William Hildred: "During the post-war years, despite the fact that costs of equipment, fuel, labour, overhaul and everything else have been rising continuously, the cost of production of our basic commodity, the seat-mile, has been decreasing continuously. This is no coincidence."

As regards safety, many of the problems which arise on the modern transport aircraft are so complex and specialised that even with the greatest help from the manufacturing industry, professional engineers (including a number of specialists) are essential within the airline.

As regards economy, it is more often than not a very tricky matter to decide what should be altered to improve the overall operating economics, with relation to both reduction in cost and increase in revenue. It has proved essential to have engineers who can weigh the balance between the frequently conflicting requirements of maintenance, operations, and even the manufacturer! Experience has shown that in this field of his work the airline engineer can continuously produce economies amounting to many times the cost of his salary.

In the airlines on the other side of the Atlantic the work he covers is called "engineering" to differentiate it from "maintenance." In this country, as "engineering" is used in the general sense to cover both activities, the word "development" is used. This undoubtedly leads to confusion about the responsibilities of the professional engineer in the airlines in the United Kingdom and a lack of understanding, particularly in less technical quarters, of the vital part he has to play in the safety and economics of the airline.

The "airline engineer" has to be expert, therefore, in the requirements of not only maintenance, but also flight operations. He must cater for the needs of, and deal with the problems arising from, equipment handling by traffic and catering and from the commercial requirements of schedules and operating plans. He must be able to deal with the designer and manufacturer on equal terms. He must be able to work with the safety and economic implications of what he is doing always in mind. And because of the indirect way so much of his work has to be done, he must have more than a smattering of the principles of good administration.

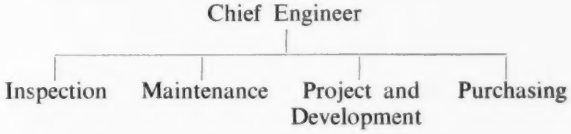
Organisation

The scope of engineering in the airline was dealt with by Mr. Shenstone in his Anglo-American lecture[1]. In this lecture, Mr. Shenstone commented on the confusion of terms now existing both as regards engineers themselves and their organisations or administrative structures.

Notwithstanding substantial variation between the world airlines in titles of their engineering personnel and the corresponding differences in responsibilities, the same general pattern has emerged on both sides of the Atlantic for dealing with the complex technical problems confronting present-day airline operation. The "airline engineer" is to be found in each of them acting as the central source of technical knowledge for the airline and the reservoir of the operator's technical experience.

The broad pattern (in which B.E.A. is now similar to most of the large scheduled airlines) follows the lines of division of responsibility into two main parts: maintenance and "project and development"—or in American nomenclature, maintenance and "engineering." In B.E.A. these two functions are brought together under the Chief Engineer, while in American airlines, for example, the two functions are either separately responsible to the executive head of the airline or, still separate, are part of a larger function such as Operations.

In B.E.A., the responsibility for the total Engineering activity is arranged thus:



The B.E.A. Annual Report for 1952 gives the following summary of the Engineering activity:

1. To keep the aircraft fleet flying for the maximum practicable proportion of every day.
2. To improve the aircraft in the fleet so that they can do their job more effectively and more economically.
3. To develop new types of aircraft for the airline. This involves both original work and close collaboration with manufacturers and other airlines.

The Maintenance and Inspection functions are concentrated on the first of these activities. Maintenance is responsible for the continuous maintenance and overhaul of the equipment, for the operation of the hangars,

workshops and stores and for the administration of the labour force. Inspection provides the overall quality control.

Project and Development, while wholly responsible for items two and three, shares responsibility for the first, helping to "Keep the aircraft flying" by the day to day provision of solutions to technical problems which arise, and the development of the equipment and techniques for both its maintenance and operation.

Purchasing provides a specialist service for the contracting out and buying of spares, materials, overhauls, modification parts and so on.

PART II—DEVELOPMENT IN SERVICE

The only way to get new equipment to the stage when it can be operated continuously day in and day out with both safety and economy is by development in service.

By the time equipment of brand new design, whether complete aircraft or component parts, is delivered to the first operator, the maker and the legislative authorities should have provided for its safety in initial operation. It is only by the most energetic development in service however, that safety can be maintained and the economy of operation assured. This will cost the first operator a lot of money.

The fundamental importance of this is insufficiently appreciated, both within the airline and outside.

The question is often asked: why can't the manufacturer do all the development? The answer is that he can up to a certain point, but beyond that point there is no alternative to development in service by the airline.

Development in service means two things:

(*a*) Development of the equipment on the basis of actual use in service—maintaining or improving the safety of the equipment by modification or alteration of techniques, while continually reducing its operating cost.

(*b*) Alteration of the equipment to meet changing needs.

Many airlines can operate with well-tried equipment (*i.e.* equipment which is old and perhaps, therefore, non-competitive); they have no need for doing development in service.

All the leading airlines in the world, however, are now doing a great deal of it; and those who are the first operators of new aircraft must do the most.

The Development Organisation in B.E.A.

Engineering development in B.E.A. therefore covers:

(*a*) The solution of the daily and long term technical problems arising everywhere within the airline, and the provision of the necessary technical information and advice to keep the aircraft flying;

(*b*) Development of the existing equipment in service and of techniques for its use to give maximum efficiency;

(*c*) The introduction of new equipment to improve on the old.

When B.E.A. was first formed, we were faced with the initial operation of an assortment of pre-war aircraft types and the immediate introduction of the Viking. In addition, there was the task of preparing the way for the introduction of the Viscount.

It was decided at the outset that the most practical result would be achieved if project work on new equipment and the current development of existing equipment were combined under one responsibility. Wherever possible, therefore, each development engineer combined responsibility for new equipment with current responsibility for equipment of a similar kind in service. In this way, competent liaison between user and manufacturer could be established and the most realistic requirements for new equipment formulated.

In the absence of men with the necessary basic training or experience in airline development work, the development organisation in B.E.A. had to be built up from scratch; wherever possible engineers with actual flying experience were chosen. Starting with a handful of men in 1946, the Project and Development Branch has grown to 127 members, and its responsibilities have broadened to include helicopters. The deployment of this manpower on the different aircraft types is shown in Fig. 1.

The continuance of so large a proportion of the effort on such a well-tried type as the Dakota was caused by changes which took place in the original equipment plans around 1948. Originally, the Dakotas—wartime machines requiring much alteration and development in service—were to have been replaced by early 1951 as part of the policy of flying British. Under the revised equipment plans, however, a large fleet of Dakotas was to be built up and a separate engineering base established at Renfrew, thus calling for a separate development staff up there. A big part of the initial task on these machines was the preparation of drawings for alternative parts which could be made in the United Kingdom to save dollars, and as this began to die down the Pionair conversion programme started, requiring a great deal of development effort within the airline. The particular point to note here is that these Dakotas were not civil aircraft supplied direct to the operator with full manufacturers' backing. We had to build up the fleet, maintain, operate and develop it almost entirely from within the airline.

The work of the development organisation in B.E.A. covers, in addition to the subjects already mentioned, such matters as: the procurement and technical acceptance of new equipment; technical and economic studies of new aircraft types and projects; and the provision of technical instructions to various groups within the airline who use the equipment, such as Maintenance, Traffic, Flying Staff and Catering.

Direct comparison with the engineering development staffs of other airlines would be interesting, but

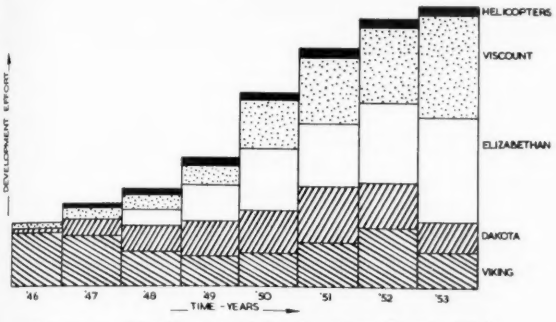


FIGURE 1. Distribution of development effort in BEA.

unfortunately the variations in function and structure make such a comparison impracticable. Enquiries have shown, however, that the job in B.E.A. is being done with a much smaller staff than in the other large airlines, which in some cases employ up to twice as many development staff as B.E.A. to do the same kind of work. In drawing any comparison, moreover, it should be remembered that over the comparable period most airlines have been using equipment introduced and tried out in service by someone else. In its short life B.E.A. has been the first operator of three entirely new aircraft types which did not derive from types with substantial current airline service (as the DC-6 was derived from the DC-4).

Maintenance

Again the pattern adopted by most airlines is employed in B.E.A., the maintenance function covering both routine maintenance of the aircraft out on the routes, and overhaul of equipment as well as aircraft. There are certain differences however in the way in which responsibility is broken down within the maintenance function, in addition to such points as method of controlling the stores, use of inspectors and so on.

The major difference between B.E.A. and other airlines lies in the use of the incentive bonus system. Here, while experience has shown that such a system can reasonably be applied to the process of aircraft maintenance and overhaul and be well worth while, a good deal is still being learnt on the detail application of the system to the peculiar requirements of aircraft maintenance.

The incentive bonus scheme was first introduced after the Vikings had been put into service, and with it came a maintenance system of centralised planning and rate-fixing. The emphasis was on planning all work in detail before the aircraft came in for maintenance or overhaul, each man being given detailed instructions of the job to be done and how to do it. This particular approach to aircraft maintenance was developed while the Viking itself was being developed and was settling down in service. Thus, as the particular idiosyncrasies of the Viking became well known and the sort of troubles encountered on all new aircraft were dealt with, so the maintenance on the aircraft became more and more a matter of standardised routine.

The maintenance organisation and procedures developed alongside the Viking and, with less need for flexibility as the aircraft settled into service, they became more rigid and inflexible. There were dissentients who felt the maintenance system was becoming too rigid to cope with the unpredictable arisings on new equipment, when first the Elizabethan and later the Viscount started their life in service.

The difficulty with a system which depends on knowing too precisely in advance the work to be done on each check before the aircraft comes in, is that it can lead to lack of flexibility on the job, difficulty in making last minute adjustments, and difficulty in incorporating the modifications on which the ultimate success of the operation depends. It can be seen also that a danger which has to be guarded against continually, is that of vesting too much "know how" in the rate-fixing and planning office and too little in the man on the shop floor. It could lead to inaccurate diagnosis of faults and unnecessarily expensive rectification action, particularly in new equipment.

The process of developing the maintenance methods with an eye to these difficulties has been proceeding for some months now, at the same time retaining the very real advantages of the incentive bonus scheme.

The maintenance task in B.E.A. has been unduly complicated by the coincidence of the introduction into service of the two new aircraft types with the move into the new Engineering Base at London Airport.

The two basic factors determining the cost of maintenance in the airline are, of course, the amount of work needed to be done on the equipment and the cost of the replacements (spare parts and materials) required.

The actual cost at any time arising from these two factors (amount of work and cost of replacements) is a reflection of a number of things, in particular:

1. Suitability of the equipment for operational wear and serviceability.
2. Suitability for ease of maintenance.
3. The total flying hours accumulated and the amount of experience obtained and development done as a result, particularly on new equipment.
4. The administrative skill in planning the maintenance work on the checks.
5. Technical skill in deciding just how much work need be done.

While manufacturing production methods are in many ways applicable to aircraft maintenance and overhaul, it will be seen that the above five items introduce serious variables not generally present in straight manufacturing processes.

The maintenance schedule is the basic document in the airline from which all routine maintenance work stems. It details the inspections, removals, adjustments, tests and cleaning which have to be done at each maintenance check. It also lists the current overhaul life of all time-lifed components.

A great bugbear in the airline is the "special check" which appears on the maintenance schedule because some trouble has been experienced. It is so easy for the airline staff to call for a special check, or a check

of all aircraft within a certain time. The Air Registration Board and the manufacturers also ask for such checks. Each time the maintenance cost goes up, and the check time cycle is affected.

It is much more difficult to decide to remove special inspections or other checks from the maintenance schedule than to call for them. This is where a continuous co-operative effort is required between the Inspection, Maintenance and Development staff on the basis of experience.

To keep down maintenance costs, the operator requires equipment which is easy to maintain and which can be developed to have long life between each operation. As well as components with long overhaul lives, the operator requires, for cheap maintenance:

1. Long periods between inspection of any particular item or assembly.
2. Long periods between adjustments.
3. Long periods between tests.
4. Long periods between cleaning and greasing operations.

When the designer has done his best in the first place, and after the equipment has had initial testing and improving and has been bought by the airline, the only way in which the work set by the maintenance schedules can be reduced is to make the utmost use of experience in operation in extending all these periods. This means continual critical review of the work done, rapid development action on troubles arising and rapid incorporation of modifications to develop the efficiency of the equipment. Adequate effort put into this work pays handsome dividends.

Diagnosis of Troubles During Maintenance

Any system of aircraft maintenance, however good, will fall down if the daily and hourly diagnosis of troubles is poor. The cost of maintenance on new equipment, instead of being steadily reduced, will stay static, or even rise, if rapid and intelligent diagnosis is not done.

Troubles arise at all stages of the game: on the Tarmac just before flight, while the aircraft is on a routine check, on overhaul, in the workshops. The first essential is that the fault should be located accurately and expeditiously. This is particularly important on complicated assemblies or systems where the particular fault could be in any one of several different locations.

This accurate and expeditious diagnosis of faults and their precise location demands three things:

(*a*) Trained competent personnel.
(*b*) Adequate test equipment.
(*c*) Flying equipment so designed that fault finding is practicable.

The airline must provide the first two—the manufacturer the third. Inaccurate diagnosis caused by lack of suitable test equipment, lack of skill on the part of the mechanics, or impractical equipment, leads to increased costs and reduced revenue in a variety of ways and in the most alarming manner. An example can be found in the time wasted, which puts up the elapsed

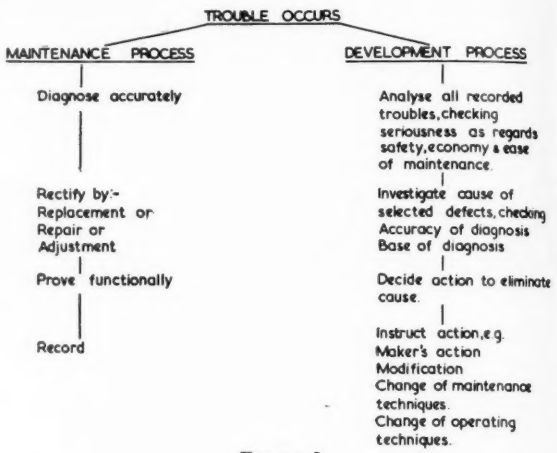


FIGURE 2.

time of the check and increases its cost, also delaying the aircraft on service; similarly with the changing of a suspected component, the testing system, and the changing of other components because the fault has not been found. This latter example can add to the pile of components returned to the workshops for overhaul before life expiry, starting up a costly sort of chain reaction which can have its effect on delaying other aircraft because all the spare components have been used up or are being overhauled.

To quote another kind of example, a fault occurs on the engine or aircraft on final check before flight and, through bad diagnosis, several engine runs are required before the fault is cured; or again, because certain kinds of faults have been incorrectly diagnosed, additional test flights may be required at considerable cost (*e.g.* £100 or more per hour for the Elizabethan).

Diagnosis—or, more colloquially, fault finding or "trouble shooting"—is directed at finding the location of the fault in the quickest possible time so that it can be rectified in the most convenient manner, *e.g.* replacement of faulty component, adjustment or repair. Diagnosis is a fundamental part of the continuous process of maintenance, aimed solely at getting the equipment serviceable quickly so as to keep the aircraft flying.

Diagnosis is not intended to discover the root cause of faults, although it will sometimes expose them; this part of the work demands a totally different approach and may easily take weeks in complicated cases. The job of finding the root causes of faults and troubles is a fundamental part of the process of development. By efficient diagnosis however, inspection and maintenance staff have shared considerably in this development process, pointing out weaknesses in design and improving methods.

Investigation of the Root Causes of Troubles

This part of the development activity covers not only troubles, defects and difficulty experienced by Maintenance, but also by others handling and using the

equipment, *e.g.* Flying Staff, Traffic, Catering. It provides the material and experience for the alteration of equipment and techniques in service and also, the vital experience on which requirements for new equipment can be based.

This experience cannot be obtained first hand by the designer, so one of the problems is finding the means by which it can best be transmitted to him by the operator. We have moved a long way towards this goal by making our development engineers responsible for both current development (including this investigation work) and the procurement of new equipment.

Of course troubles sometimes arise, particularly with new equipment, where routine rectification by Maintenance is not enough by itself without immediate investigation into the root cause; in these cases the development staff is called in at once. This has two effects of economic benefit to the airline: in the first place it helps "keep the aircraft flying"; and secondly, the development staff get to know first hand the sort of things that are really hurting the airline, costing it money and causing dislocation.

Thus, from the initial occurrence of the trouble, there are two chains of action: the first is the diagnosis of the fault and its immediate rectification, with the end product that the equipment is put back on service in its original state ("keeping the aircraft flying"), while the action taken is recorded by various means so that subsequent investigation can trace back on what was done; the second chain is the establishment of the cause of the fault and taking action to eliminate its recurrence. Fig. 2 shows the two processes.

Good defect diagnosis demands maintenance and inspection staff who must be skilled at their particular trade and trained in the idiosyncrasies of the particular flying equipment being used. The A.R.B. licence standard is a good basic yardstick for this.

I have already mentioned our difficulty with the maintenance system for accurate diagnosis of faults; the training programme now under way will assist in building up the required standard of skill for this work.

Good technical investigation demands first class development engineers, who in certain cases will be specialists. We have found that a good man with an engineering degree and several years' practical experience on design or other engineering in the Aircraft Industry will, even so, take a year or so to reach the standard required for this work.

Difficulty of doing Development within the Airline

The necessary development of new aircraft and equipment after it is designed is in three parts:

Makers' tests and trials
Proving and familiarisation trials
Development in service.

A great deal has been said and written on the subject of the design and supply of equipment so that it does not require development in service, *e.g.* components already proved to run long lives. The facts of life are, however, that in the air transport business the quantities of new equipment likely to be sold are comparatively small, and all pre-service trials and testing will put up the initial cost of each piece of equipment. There is, therefore, an economic limit to the amount of testing and proving which can be done by the maker. This limit must, however, be sought and in our experience there are cases where insufficient pre-service testing has been done; on the other hand, experience shows it to be very unlikely that the most extensive bench testing will provide an automatic long life in service with complete freedom from teething troubles.

The amount of proving of a new aircraft before service is also a matter of economics—it will cost a lot, for example, to do extended proving flying of whole aircraft. Yet there is no other way of seeing how the equipment will perform.

On the Viscount and Elizabethan 200 hours' proving flying was done on each, apart from makers' trials and operators' training. Experience shows that no new aircraft of any size or complexity should be put into service with less than this.

It is extremely important that this proving flying should simulate precisely the conditions of operation in all respects, and for this reason there is no doubt that the first operator should do it, however it is financed. The flying should be done to a fixed schedule and timetable, and every operation expected to arise in normal service should be carried out. If this method is not adopted and the flying is done on the experimental flying basis, the effect of things going wrong or difficulties being encountered will not be seen in the proper perspective and the money put out for this flying will largely be wasted. We have had experience of both methods and are in no doubt as to the lesson to be learnt. In these trials the maintenance must also be done to a pre-arranged schedule and, in fact, to the maintenance schedule which will be used in service and the actual work should be done by airline maintenance personnel.

With new aircraft there has been substantial development work to do in the past while the first few production aircraft were in service, and it is more than likely that this will hold good in the future, notwithstanding the work done by legislative authorities and the manufacturer before delivery of the first aircraft. The main reason for this is again economic—there is no substitute for the experience gained in many hours of use. As a result, though, it means that while the first operator is getting experience on the first batch of his new aircraft, development work frequently involving extensive flying will have to be done.

The prototype aircraft are useful for this work only if they are sufficiently representative of the production batch. This has not always been so and special pre-production prototypes have been built—a very expensive process.

In B.E.A. a Viking was kept aside for development flying during the first two or three years of operation of Vikings as a new type, for use on work which could not be done on line service. With the Elizabethan fleet, B.E.A. is severely restricted because there is no aircraft allocated for development, the pre-production prototype

Elizabethan being used for other purposes and, as there is no further production, the possibility of development and test work being done by the makers on the production line is ruled out.

The B.E.A. development Viking meant some £40,000 operating capital on which revenue could not be earned and represented 1/35th of the fleet. One Elizabethan would be 1/20th of the fleet and a very much larger capital sum.

As part of the introduction of a new type, therefore, it is essential that the government finance of the project should include a development aircraft for the first three years (say) of operation of the new type.

The much more difficult and costly task, not even capable of solution by "just getting the money from somewhere," is that of development in service. A separate development aircraft can only be used for tests and trials involving relatively few hours of flying. Development in service carries big financial rewards, but can only be done on the basis of large numbers of hours' use; the real proving of a new aircraft, therefore, demands many hundreds of hours in actual service.

Development in service is essential on all new equipment and yet is very difficult indeed to do. Any disturbance of standardised maintenance or flying schedule routines will be costly on manpower or in time the aircraft is off service, yet a modification or trial of a new piece of equipment, or change in technique, may lead to very substantial reduction in maintenance costs or time off in service. More important, the reduction is not just an isolated case at one moment in time but probably keeps recurring for the rest of the life of the equipment.

We thus have the paradox that the maintenance and flight operating routines must be continually disturbed in order to discover or try out the very necessary means of improving them.

Much of the service development work which has to be done is associated with long life of either working components or of static parts for damage, wear and, of course, fatigue. Trials have therefore to be made over the whole of the "life" of a number of units. This problem of development in service is by far the most difficult engineering problem the airline has to face. It is a continuous process which must go on until the equipment has settled down into reliable and economic routine service.

Modifications and trials of various kinds which are designed to improve the equipment on the basis of service experience are a very necessary evil, therefore—necessary, because of the economic advantages which result, and evil because of their dislocating effect on the routine of maintenance.

The period of time over which this "development in service" will take place on a new aircraft cannot be stated precisely; it will depend on many factors, such as the skill with which the aircraft has been designed and the number of already proven components used in it. It is reasonable, however, on the basis of experience, and assuming a high standard of design for maintenance, that extensive "development in service" will be

REQUEST FOR MODIFICATION

ENGINEERING DEPT. - P&D BRANCH

REQUESTED BY: P&D | A C TYPE: VISCOUNT 701 | No.: A 60

REQUIREMENT TO INTRODUCE A GROUND/FLIGHT TEST AMMETER IN THE PROPELLER DE-ICING CIRCUIT.

PRELIMINARY ASSESSMENT. PROJECT & DEVELOPMENT BRANCH

DESCRIPTION OF MODIFICATION TO INTRODUCE A GROUND/FLIGHT AMMETER IN THE PROPELLER DE-ICING CIRCUIT INSTEAD OF THE EXISTING MODEL 225 AMMETER. THE FOUR ST CURRENT TRANSFORMERS ARE REPLACED BY FOUR TR3 TRANSFORMERS HAVING 3 TURN PRIMARY WINDINGS, AND MODEL 225 METER WITH A SPECIALLY CALIBRATED THIN SCALE GIVING FSD FOR BOTH GROUND & FLIGHT CONDITIONS IS FITTED. A MODEL 110, 12 OHM. RESISTOR IS FITTED IN THE SECONDARY CIRCUIT FOR 'FLIGHT' OPERATION AND SWITCHED OUT FOR GROUND TEST.

COMMENTS T.I. REQUIRED. PRODUCTION CONTROL TO RAISE IMMEDIATE R.T.P. TO COVER PURCHASE OF T.I. SET OF PARTS AS FOLLOWS.

QUANTITY 1 THIN SCALE AMMETER MODEL 225
QUANTITY 4 TR3 TRANSFORMERS
QUANTITY 1 MODEL 110 12 OHM RESISTOR

REFER TO SPECIFICATION TS 7866 ON ORDER

COST
Bought Parts — AS ABOVE. — Per A/C £6.
Installation — 2½ MAN HOURS. — Per A/C £1. 5. 0
Payload Loss 1/8 lb. at £ 86 x 10 years — Per A/C £35.
Extra maintenance costs for ____ years — Per A/C N/L
COSTS FOR FLEET (26 A/C) £ 1046. 10

SAVING
Disposal of parts — Per A/C —
Payload gain ____ lb. at £ ____ x ____ years — Per A/C —
Saving in maintenance costs for 10 years — Per A/C 475
SAVING FOR FLEET (26 A/C) £ 12,350

NET ~~COST~~ SAVING FOR FLEET OVER 10 years £ 11,303. 10

PREPARED BY B J ELKINS | CHECKED BY A J COPE | DATE 9. 6. 53

STATEMENT BY PROPOSER OF OPERATIONAL OR COMMERCIAL BENEFITS

THE PRESENT SYSTEM OF GROUND TESTING IS NOT POSITIVE AND FLIGHT SNAGS CANNOT IN MANY CASES BE CHECKED OR RECTIFIED WITHOUT FLIGHT TESTING.
THE ACTUAL MAINTENANCE SAVING DEPENDS ON THE FREQUENCY OF THIS TYPE OF DEFECT. THE ABOVE ESTIMATE HAS BEEN MADE ASSUMING THAT EACH AIRCRAFT WILL REQUIRE A TEST FLIGHT FOR THIS REASON ONCE EVERY TWO YEARS

PROPOSER B J ELKINS

C.P.D.E.'s AUTHORISATION pp. W B SHAN.

FIGURE 3.

needed over a period of at least three years before a new aircraft can be said to be running economically.

This apparently long period, three years out of the ten years usually taken for the amortisation of capital outlay on new aircraft nowadays, arises from: the need to get in sufficient service hours to extend the maintenance schedule periods; the time required to make trials of modifications or longer lives; and finally, the time required to incorporate the vitally necessary modifications into all the equipment.

All this work has to take place while the equipment is in service. Development and flight testing in the more comfortable atmosphere of the prototype flight shed or experimental establishment cannot take the place of "development in service," even if time and money were available. Development in service is a very costly process because of the dislocating effect on maintenance and operating routines.

Modifications

Modifications are the core of development in service. No modification should be worked up in the development office unless it can be shown to pay off. This is the secret of the whole business—"can be shown to pay off."

It is a fact, not perhaps appreciated by many, that all proposed modifications can be judged on financial grounds. We have developed a tight but simple process for the control of modifications.

A document, the "Request for Modification Form," Fig. 3, has been evolved to show the financial result likely to accrue from each modification.

No proposal to alter either the aircraft or any part of the flying equipment can get beyond the examination stage until this form has been properly authorised. Requests for modifications are made to the development engineers, who investigate the technical and economic aspects of the proposal and complete the form. It is then submitted for authorisation before any work can proceed or money be spent. Even so, for large modifications requiring capital expenditure, further authority is required before the modification can proceed. This system is not so unwieldy as might appear. A form can be completed, authorised and the modification proceed on the same day, if need be.

The development engineers have been trained from the outset to think commercially and to produce a balance sheet for each job they are doing, showing the cost, the economic penalties and the advantages.

In the standard use of this method of modifications control, a fixed sum per lb. weight per aircraft per annum is used for each aircraft type and only altered periodically as experience dictates. When occasion demands, special calculations are made on the basis of specific routes or schedules, particularly when the first balance sheet gives a marginal result or when there is an overwhelming opinion in favour of the modification, notwithstanding a "loss" appearing on the modification balance sheet.

In our experience, the use of development engineers trained to think in terms of economics, and the insistence that all proposals to alter equipment should pass through this modification system, have resulted in enormous savings through efficient control of modifications. No separate system of weight control is necessary.

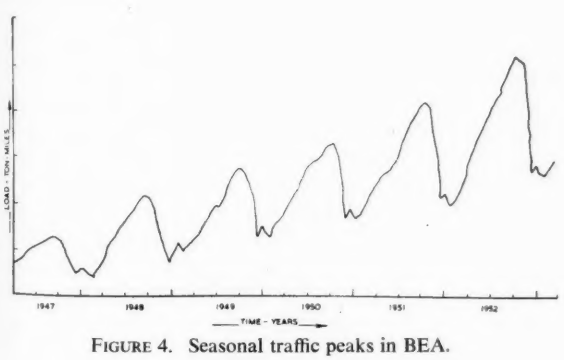


FIGURE 4. Seasonal traffic peaks in BEA.

Any system of control such as the foregoing is ineffective if the modifications which receive approval are not incorporated quickly. I have mentioned earlier some of the difficulties of doing trial installation work in the airline and the phase we are currently passing through in the problem of incorporating modifications.

During visits I have paid to other airlines in Europe and the U.S.A., I have noted that the flow of modifications in service is similar in all cases. In fact, it is interesting to see that several of the larger scheduled airlines employ more development engineers on this kind of work than B.E.A., although for several years they have not introduced a brand new aircraft into service as the first operator of the type, and in some cases have never done so.

The Battle of the Peaks

The traffic pattern in B.E.A. is highly seasonal; Fig. 4 shows the current situation. Although these peaks may be reduced in degrees by one means or another, they are likely to persist. The heavy work period for Engineering is therefore in the summer, and the problem we have not yet solved is how to deal with this situation most economically. The prospect of a solution has been confused by the introduction of the two new types so close together, and the extensive modification programme being done on the Elizabethan.

We have for some years employed the system of progressive maintenance, on which the aircraft never comes in for an annual overhaul but this work is broken down into parts done at one or another of four successive major checks. This enables a much more constant work load to be planned for hangars and workshops. It would seem, however, that in view of the seasonal fluctuation, it might enable the overall engineering costs to be reduced if some of this summer work were held over.

This highlights another problem—that of incorporating the modifications so essential for economic development. Should these generally only be put in once a year, *i.e.* in the winter, because of the traffic peaks? If this were so, development of the equipment might take much longer than the airline could afford.

The answer to both these problems is probably one of compromise—some modifications will have to be put in during the summer whatever the peaks; others can perhaps wait for yearly intervals if the cost of doing them in the summer proves too great; others again, requiring aircraft off service, will have to wait until the winter.

The continuous cycle of maintenance and operation considered against these peaks presents a formidable but fascinating problem with a very sharp economic content. It emphasises the often conflicting requirements of airline routine versus economic development.

Defect Control

To attempt to cure by modification and to prevent the recurrence of all defects, is simply not practicable or economically justifiable. It is only possible to tackle some—the problem is which?

I have shown how we control the flow of proposals for modifications, but in a sense this is a negative control. It prevents, or can be employed to prevent, unnecessary or uneconomic modifications from going forward.

The real problem is to select those which should be done and to give them the right priority. The economic control does help in selection, but the problem of allocating and maintaining the right priority is very difficult indeed.

Which, for instance, should get priority if, as so often is the case, it is not possible to do everything simultaneously? Should it be a small modification to correct a defect which has only occurred a very few times out on the routes, but has delayed an aircraft each time? Should it be a large modification required by the Maintenance Base because of excessive manpower used on overhauls in view of some continual failure, but which has not delayed an aircraft? Or should a modification insisted upon by the operating side, but difficult to measure economically, have preference?

In general, the cause of service delays must get priority and a simple method would be to select those troubles causing the most delays and deal with them.

The problem becomes acute, however, when the scatter of different causes is very great. Appendix I gives a facsimile of the engineering service delays for one month on one aircraft type. The nature of the problem can be seen from the wide scatter of kinds of trouble. The manpower is not available to investigate and take action on more than a few of these. Month by month analysis may disclose recurring items, which can then be dealt with. Appendix II shows an analysis over six months, indicating that the spread of isolated troubles is even wider than indicated by Appendix I.

Many systems, mathematical and otherwise, have been tried out by various airlines to beat this problem. In B.E.A. we are continuously revising our views and methods, but so far we have found the best method of control to be a judicious compromise, making full use of defect summaries and statistics in combination with the actual experience of what is hurting most on the job. The views and experience of the men in maintenance and inspection count a good deal in this work.

The major difficulty is that of getting the modifications incorporated into the equipment.

I remember examining this problem on the spot with the staff of one American airline and following a low priority modification in the routine pipeline, assuming that its absence was not pinching quite hard somewhere. To our mutual interest the time from the drawing board to the incorporation in all the fleet and spares was $2\frac{1}{2}$ years! On the other hand a whole fleet has been modified in a day or two when the alternative was grounding! The need to set priorities and control and progress modifications within the continuous operating cycle in the airline is therefore of first importance, particularly when the modifications bring with them substantial economies. The need to design them out in the first place is paramount.

Life Development

The importance has been shown of the rapid development of overhaul lives in service when new equipment is being introduced. To assist in this work records are maintained of defects on time-lifed components in the form of charts, a sample of which is given in Appendix III.

Substantial development in the approach to this problem has taken place during the life of B.E.A.

In the early days lives were strictly controlled by the Air Registration Board and the tendency was to restrict the life as soon as defects appeared. We began to realise that it was possible to recognise a standard pattern of defect occurrence on which the overhaul life had little direct bearing, and we set out to collect the evidence to prove or disprove this theory. The results of this work were included by Mr. Hardingham, Chief Executive of the Air Registration Board, in his lecture "Maintaining Airworthiness in Operation,"[3] and they provide the basis for the interesting mathematical analysis produced by Tye and Cundall[4].

The basis of the theory is that defects do occur early in the life of groups of time-lifed components, but that the rate decreases to some minimum value with increase of life; only when the curve starts to rise again should the life be restricted until extended by development action. Fig. 5 illustrates this.

Provisioning

One of the problems which arises with new equipment is the difficulty in provisioning spare parts and equipment on an economic basis.

The problem is in three parts:

(*i*) Initial provisioning or guessing the spares likely to be needed for an initial period of operation of new equipment.

(*ii*) Provisioning against fluctuating current consumptions in service.

(*iii*) The number of spare or "float" components required to keep the maintenance cycle going while development in service is taking place.

The difficulty on the first is in direct proportion to the "newness" of the equipment, or its dissimilarity from equipment already being operated. This can only be done with experience. When the Viking was introduced recourse was had to wartime Wellington records, particularly of defects. If the new equipment is likely to be sold in quantity, the manufacturer can probably be encouraged to assist by supply as required off the production line or, as many suppliers now do for B.E.A., in providing an "off the shelf" service in return for an extra charge per item.

Provisioning against current consumption is a commercial task involving knowledge of market trends and a good deal of capital outlay, and reduction in current costs can be achieved by intelligent purchasing arrangements. Again, where the manufacturer can be prevailed upon to play his part, an "off the shelf" service is of great advantage to the operator. The task of

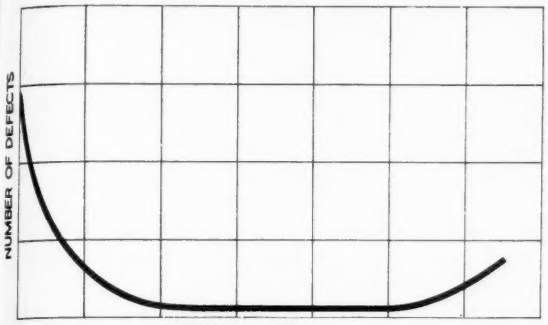


FIGURE 5.

provisioning is complicated considerably by fluctuating consumption in new equipment and a problem arises when large stocks require modifying, or even become redundant owing to the introduction of modifications.

The third part of the problem, although perhaps not provisioning in the strict sense of the word, is the deciding of the right number of components required to keep the maintenance cycle moving smoothly. The number of complicated and expensive removable components on a modern transport aircraft is very large, and over-provisioning on these can put up costs considerably. On the other hand, enough spare components must be available during overhaul to enable routine maintenance of the aircraft to proceed without delay. Low lives between overhaul or troublesome components bring with them considerable indirect increase in cost, because of the larger floats required to keep the aircraft flying.

Manuals and Instructions

While the process of development in service is taking place, both the technique and the equipment are in a constant state of flux. With a large fleet of aircraft and area of operation there are large numbers of people who need to know of these changes, albeit in different ways.

The operator has to provide adequate technical literature to enable the operation, handling and maintenance to be done expeditiously and safely.

Experience has shown that the dissemination of this sort of information is a specialist task and that on economic grounds it forms an essential part of the engineering development process.

Each change is, of course, known to some specialist in the organisation, and anyone encountering it could perhaps find out about it by looking up the modifications documents or by asking the right person—but apart from the safety aspect this would be a wholly uneconomic process. Centralised preparation and distribution of instructions on changes in techniques and equipment modifications are therefore economically justified.

The basis of this work is the makers' maintenance and overhaul manuals, and the work involved in keeping them up to date on new equipment is formidable.

Instructions for flight operation of the equipment are dealt with in the same way, the operating manuals in B.E.A. being produced by the Engineering development staff.

Whenever a change in technique is decided upon or the equipment is modified, the development staff draft technical instructions for issue to maintenance, flying, catering or traffic staff, as appropriate, thus ensuring consistency and safety throughout the whole airline. These instructions are issued over the authority of the official responsible for each function; within Engineering they are issued through the Chief Inspector. The general system used is arranged on the lines of that used during the war in Air Transport Auxiliary for the issue of instructions on handling varied types of aircraft, and the job is organised more on the lines of a newspaper office than a book publisher, except perhaps that the material is handled in a somewhat less sensational manner.

The more new equipment there is the more technical instructions are required, as the staff concerned in B.E.A. are now finding with the new aircraft being introduced into service.

This subject is a difficult one for the directing authority of the airline, particularly in time of economic stringency, as on the face of it a number of people pushing out paper instructions would appear to be unjustified. Yet, in fact, apart from the safety aspect (and with new equipment the provision of adequate technical instructions is vital), this work is providing substantial economies in preventing large numbers of people wasting time finding out how or what, or doing things incorrectly with the consequent cost arising from the trouble caused.

Training

The necessity for adequate technical training of airline personnel of many different skills cannot be overemphasised. For flying staff this is obvious, but the successful, safe and economic operation of modern complex air transport equipment depends upon people with many different skills, all of whom must be fully acquainted with the best methods of dealing with the equipment in their care. I have already commented on the B.E.A. experiment in "productionised" maintenance and the skill of the men on the shop floor. In the early days of B.E.A. a comprehensive training scheme was under way at Aldermaston in conjunction with B.O.A.C., but it was subsequently disbanded and the pendulum (as such devices have a habit of doing) swung much too far the other way. Now, training courses on the new aircraft and equipment for staff of many different skills are being undertaken which cannot but have beneficial results on the economics of the airline. Possibly the pendulum will swing too far again and these courses prove too lavish, but with two new aircraft in operation simultaneously there is a great deal to be learnt. In due course and with new equipment being introduced at a slower rate, the majority of such training can perhaps be integrated more economically with the routine Engineering functions.

Competent training depends, of course, on adequate information and instructions being available.

PART III—INTRODUCTION OF NEW AIRCRAFT

Cost of Introducing New Aircraft into Service

In my paper "Introduction of New Transport Aircraft," read before the Society of Automotive Engineers[5], I dealt with some of the problems of costs arising with new equipment.

The most severe introduction costs arise when the aircraft is being operated for the first time. It is a comparatively simple matter to estimate and control the introduction costs of an aircraft which, though new to the airline, is already in successful operation elsewhere.

With a new aircraft being operated for the first time not only the aircraft, but everything connected with it, has to be developed. Overhaul lives will be low, inspection periods frequent and maintenance costs high. Operating and maintenance techniques have to be decided upon, developed and taught; unpredictable arisings will be high and utilisation low at first. The table in Appendix IV indicates the kind of sources of increased cost.

Standardised methods of estimating direct operating costs are likely to be misleading when comparing new and established aircraft types, if they do not allow for these new type introduction costs.

Figure 6 shows the effect of this on the normal cost curve for a brand new aircraft and recognises that economical operation will not be achieved at the beginning of the introduction of a new type. To the first operator, the economic advantages in other directions of a new type would have to be shown to outweigh the cost of introduction in the early years.

The foregoing remarks apply in varying degree to the introduction of any kind of new equipment, from radio aids and passenger chairs to ground equipment, provided that the equipment is not already in successful operation elsewhere.

In the B.E.A. Annual Report for 1952/53 one million pounds is quoted as an approximate figure for the cost to B.E.A. of being the first operator of the Viscount.

Effect of Newness

Generally speaking, new equipment seems to perform well when it is first put into service and then frequently falls into a trough of difficulty—a trough of varying and unpredictable depth. This impression of successful operation at the start can be most misleading and the cause of much subsequent acrimony. Looking back, when new equipment has appeared to behave in this way the reason is usually found to be a combination of two things; the actual newness of the whole equipment itself, and the undue and costly care which is inevitably lavished upon it during its initial operation. Throughout this stage it is necessary to be extremely cautious on the subject of how the equipment is turning out.

The reason for this effect arising from the newness of the equipment itself, particularly a whole aircraft, is obvious. Undoubtedly, however, the major cause of this impression springs from the initial care lavished upon the equipment, care which is out of all proportion to that which it can economically expect when in normal routine service. To give a few examples:—The manufacturer will have an immediate daily interest in it, particularly if there are more on the production line; instant help, backed by the resources of the production line, will be available. The operator will have spares and components for a much larger operation, and will not have developed his procedures for refinements in manpower economies. The operator's development engineers will be giving the equipment first priority, and the maintenance schedule will inevitably call for inspections and adjustments at periods wholly uneconomic under normal routine operation. If it is a new aircraft, the tendency will be for the operator to keep on it, at the outset, only the best and most highly trained personnel. Initial utilisation will be low and plenty of time will be available on the ground to attend to difficulties.

As a matter of practical experience, the real problems only begin when the newness wears off. As the hours start to pile up on the equipment itself, as economic stringency dictates its operation under normal conditions with strict economy in the manpower looking after it, then difficulties which were overcome one way or another begin to assume more serious proportions.

This sets a very difficult task for the engineers in the airline. New transport aircraft are so much in the public eye that they must be successful from the outset of going on service. A good aircraft will perform well and it is very difficult to avoid, as a result, a false sense of optimism in regard to the difficulties ahead. Inevitably the whole process I have described has to be done and, although more difficult with a troublesome aircraft, it is still a very exacting job with a good one. Not until the operator has taken delivery of his full fleet of aircraft and not until his operating utilisation is well up and his continuous maintenance routines are in full swing with

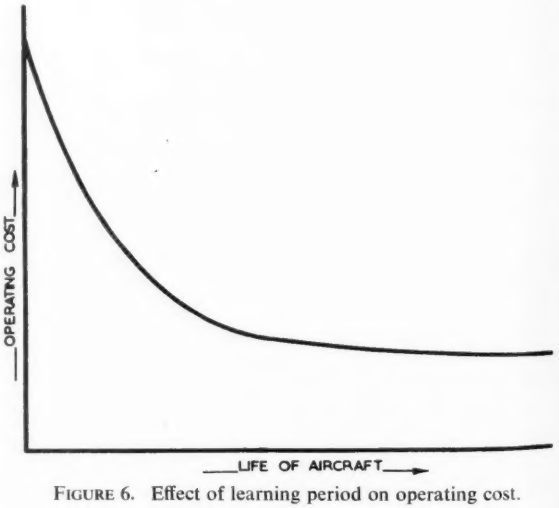


FIGURE 6. Effect of learning period on operating cost.

limited component floats, can he afford to relax. This process may take three years or so, by which time there is probably something else new in the offing.

The important attribute here is the ability to visualise aircraft or organisation troubles against the background of the full-swing economic operation and not on the somewhat false framework of the initial operations of a new type. With this goes the ability to decide from the early operations what needs to be done before the equipment is in full-swing service.

In handling this aspect of the job, the airline engineer has to carry a number of non-technical people in the airline along with him, in addition to the manufacturer. Both groups, at times, seem to have the utmost difficulty in appreciating the problem, but he must have their approval or he will not get the money or the facilities, nor will he get parts made.

Operator's Requirements

I have shown how the airline's experience of the equipment it is using, or has used, is vested in the Development staff. The future economies of the airline, and to a substantial degree the sale of the new aircraft to others, will depend on how well these requirements are expressed and how the designer ultimately reconciles them with the other, often conflicting, requirements of the overall design.

To draw up a specification of requirements or, as more often is the case in practice, to work with the designer expressing the requirements as the work proceeds, means that the individual needs must be determined from all quarters of the airline—a distillation of the operator's experience over a number of years. For this work continuity of experience is essential, while the responsibility of the airline engineer as it has already been described, enables him to act as the storehouse of this information.

The time scale of the whole thing is formidable. The operator must be able to decide, at the appropriate moment, the type and detail of the equipment he will require to have in use over a period of some 10 years, the period to start in anything up to 5 years' time.

Thus a large part of the engineer's job is a long-term investment of the first magnitude, without which the operator cannot expect to have equipment in the future really suitable for his purpose. A long-term view and long continuity is imperative, the problem being to see that it remains uninterrupted by other factors, such as organisation changes.

Operator/Manufacturer Experience

Close liaison over a very long period between operator and manufacturer is clearly the best way of getting the operator's experience into the manufacturer's and designer's hands.

In times of economic stringency, such as the present, when the need to develop equipment in service for economic operation is paramount, the operator may not have adequate manpower to maintain this liaison to the required degree.

Use of service representatives by the manufacturer goes only a small way towards meeting the problem. By this means the manufacturer undoubtedly gets to know the faults which occur, but he does not, and cannot, get to know their significance to the operator, except in the more obvious cases.

In my view this gap could be further bridged by better training of design staffs in the practical requirements of civil operation.

I would suggest two ways. First, that anyone undergoing engineering training for any aspect of civil aircraft design, manufacture or operation, should spend a period working for the operator, with the development staff. Secondly, that selected people should be sent from the drawing office and technical departments of the civil aircraft manufacturer to the operator for a similar purpose.

Difficulty might arise over the period to be selected; I would say the ideal would be two years. It might be practicable to compromise on a year, but for any smaller period than this the scheme would be nothing but a further burden on the operator. With a nucleus of people who had had this sort of experience on operational development work, the manufacturer would be in a very strong position indeed. On the operator's side, such men would be expected to take part in the work going on after a month or two, thus assisting the development engineers while gaining experience.

I commend this thought to those concerned.

PART IV—DESIGN FOR ROUTINE USE

No remarks on experience in airline engineering would be complete without reference to design for ease of maintenance and operation. Great strides in this direction have been made on both sides of the Atlantic but still more can be done; when designing new equipment it all has to be done over again. This is a vital part of the total engineering of a project I discussed earlier in connection with new aircraft. The biggest difficulty seems to be that of getting practical operating knowledge into the manufacturers' design office.

Nine Points for Detail Designers

In the following selected list of points I have attempted to summarise the experience of a large number of people doing a large number of operations a large number of times. Some of these things have been said many times before; in the context of this paper they will bear repetition.

1. *Simplicity*

Aircraft are growing more and more complicated and technical improvements are often only possible with the expense of complication. No job should be done the way it is if there really is a more simple way of doing it.

2. *Reliability*

Maintenance is so closely integrated with operational requirements (otherwise high utilisation would be

impossible) that random defects often have a seriousness out of all proportion to their technical importance. Most random defects are on components of the aircraft systems, so such components must be designed for reliability.

3. *Accessibility*

Accessibility is a most important factor in reducing the time spent on maintenance to a minimum. Accessibility is likely to get worse as performance increases: pressurised fuselages, laminar flow wings and the general trend towards higher speeds and reduced drag all militate against it. To some extent this effect may be mitigated by the grouping of like components, with large access panels to each group. An important thing for the detail designer to know is what will have to come off and when, in the maintenance cycle. I wonder how many know this?

4. *Replaceability*

It is inevitable that defects will occur and when they do, that rectification is almost invariably by changing components. In addition, all components must be changed at life expiry. Ease of removal and replacement of all components is therefore of great importance and not nearly enough use is made of devices such as anchor nuts. Apart from other considerations, the use of such devices often makes it possible for the job to be done by one man instead of two. All parts liable to wear should be easily replaceable and normally bolted rather than riveted.

"Replaceability" should not be confused with accessibility. I have seen accessible components almost impossible to replace, and components wonderfully easily replaceable but only capable of being got at with a drinking straw until other more permanent apparatus had been removed.

5. *Interchangeability*

The importance to the operator of interchangeability of components and parts cannot be over-emphasised. With the systems of maintenance by replacement already mentioned, interchangeability becomes a serious matter.

I think the word "interchangeability" itself is open to some misinterpretation. The manufacturers usually take it to mean that any one of the particular components can be checked to fit a reference jig, or even that the part has been made on a jig which has itself been checked to some reference. To the operator it simply means that a part or component can be taken off one aircraft and put straight on to another with no drilling, reaming, filing or other wangling. There seems, at times, to be all the world between these two interpretations.

Of course, on most aircraft a few components such as wings, tailplanes and undercarriages, are interchangeable in this way; so are some of the nuts and bolts. It is the lack of interchangeability on so many of the other things which worries the operator.

6. *Repeatability*

With "productionised" maintenance by replacement, the minimum amount of selective fitting or special adjustment is essential. All replaceable parts and components should be capable of being removed from one aircraft or assembly—or taken straight from a test rig—and of giving the same performance when put in another aircraft; control surfaces, certain kinds of electric apparatus and mechanical gear involving linkages are examples. The serious case of this sort is the kind of apparatus which, after being changed, requires a special test *in situ*, such as doing a ground run before it can be passed for flight. The worst of all is the case where a test flight is necessary, with all its attendant delay and expense.

Replaceable components should therefore give a repeat performance within acceptable limits, without any special selective work or tests being required.

7. *Robustness*

Remember that a civil aircraft has to last at least *10 years*, and in that time many operations will be carried out hundreds or even thousands of times. At an annual utilisation of 2,000 hours per aircraft, this represents 20,000 hours in ten years. On our routes the average duration of flights is about two hours, so such jobs as opening and shutting access panels to fuel, oil, water and other servicing doors will be done 10,000 times in the life of the aircraft. Doors will be opened and shut and sills walked on; freight holds will have bulky and sharp articles thrown into them a similar number of times. All parts which come into this category should be designed with sufficient robustness to withstand, with easy maintenance, the sort of handling they will get over this period, or to withstand such handling over a shorter period and then be capable of straight-forward replacement.

8. *External Servicing*

The normal servicing between flights often has to be done in a very short time—20 minutes at peak periods. It is therefore essential for all external servicing to be really fool-proof, and the use of special tools should be avoided. Remember also that those jobs must be done in the open under all weather conditions, and that many such operations, for example, toilet and domestic water servicing, are done by unskilled operators, who, *by union rules*, are not allowed to wield even set spanners. If any sort of tool is necessary a tradesman must be called in. The advantage of grouping servicing points must be considered, but it is not essential, for it sometimes leads to congestion and often involves long pipe runs.

9. *Control Cabin*

The control cabin has someone in it for a large proportion of every day. The pilot spends most of his working life in it and has many meals there; mechanics and inspectors spend a great deal of time in it. All possible crevices for dirt and foreign bodies to catch up should be eliminated; no holes through which things can fall should be allowed in the design (cherry stones do not improve the operation of the throttles!). The clean appearance of the dashboard and controls and front compartment of some modern motor cars is the sort of thing required.

BRITISH EUROPEAN AIRWAYS

AMBASSADOR
SERVICING DEVELOPMENT TRIALS

TRIAL Nº 10

OPERATION:-REMOVAL & REPLACEMENT OF NOSE WHEEL RETRACTION JACK.

REMARKS:-[1] NOSE WHEEL DOORS NOT FITTED.
[2] HYDRAULIC PIPES NOT CONNECTED.
[3] NO HYDRAULIC FLUID IN SYSTEM.
[4] AIRCRAFT ALREADY JACKED UP.

AIRCRAFT:- 2 ND. PRODUCTION
OBSERVER:- E.R.MAJOR.
DATE OF TRIAL:-25.10.51.

OPN Nº	OPERATION	Nº OF MEN	TIME MINS.	REMARKS
1	REMOVE SPLIT PIN AT TOP END OF JACK [1/8" DIA]	1	10	THIS SPLIT PIN IS VERY INACCESSIBLE: A SAFETY PIN WOULD BE EASIER TO REMOVE & REPLACE.
2	REMOVE SPLIT PIN AT BOTTOM END [1/8" DIA]	1	2	
3	REMOVE SPLIT PINS AT PIVOT [2 X 3/32"]	1	4	
4	REMOVE PIVOT LINK BOLTS & LINKS.	1	4	
5	REMOVE LOWER ATTACHMENT BOLT.	1	2	IT IS VERY DIFFICULT TO TAP THE END OF THIS BOLT WITHOUT DANGER OF DAMAGING THE HYDRAULIC PIPES IN THE IMMEDIATE VICINITY. AN EXTRACTOR WOULD OBVIATE THIS.
6	REMOVE UPPER ATTACHMENT BOLT	1	2	
7	REMOVE JACK.	1	1	

TOTAL TIME :- 25 MINS.
REPLACEMENT - REVERSAL OF ASSEMBLY
TOTAL TIME - 25 MINS.

FIGURE 7.

To sum up:

1. Keep it simple.
2. Use a reliable component.
3. Can you get at it?
4. Can *one man* replace it?
5. Will it come off one aircraft and go straight on to another?
6. Will it perform to standard when replaced or adjusted without fiddling?
7. Will it last?
8. Can it be done in the cold and wet without special tools?
9. Can it be cleaned easily?

Servicing Development Trials

One of the problems arising on new equipment is that of learning quickly the best techniques for maintenance and finding out as early as possible whether the design is satisfactory from this point of view.

It is too easy to say that the design staff should foresee all this, but there are always bound to be snags arising when a new machine of any kind is first built. Besides, very few aircraft firms have had such long and continuous use of their equipment in civil operation as to be able to foresee all the snags in the detail design stage.

To establish the basic procedures for maintenance of each part of the aircraft, and to check on the suitability of detail design and component accessibility, we instituted a series of checks to be made on the prototype aircraft and, where this was not representative, on the production line at various assembly stages.

The checks were devised actually to carry out each individual maintenance job on an aeroplane to find out the difficulties involved: techniques and tools required, sequence of operation, and so on. The operation was witnessed by an engineer and timed. This process proved singularly successful and of great value in the introduction of the Viking.

We try to make a practice of doing these trials in the earliest possible stages of any new equipment on order—from new type aircraft down to individual components.

The ideal would be to do such trials on every component part of a representative prototype before production *design* begins. That cannot be done for obvious reasons. However, a great deal can be done on a reasonably representative prototype and during early production.

A complete schedule of these trials was evolved for the Elizabethan but many desirable changes could not be made. The process was also carried out on the Viscount.

Although they were somewhat sceptical at the start, we have found manufacturers co-operative in this work when they have realised that it is a means of getting first hand knowledge on how their equipment will work in practice, so that they will be able to produce a more saleable product. Also, by witnessing the trials and discussing the results, the manufacturers' design staffs have found they can get first hand experience on their own designs cheaply and with a minimum waste of time.

The report sheet (Fig. 7) for each servicing trial includes the name of individuals witnessing the trial and description (*e.g.* remove and replace nosewheel assembly or pressure door seal or freight door sill, and so on), the time for removal and replacement, number of men required, tools used, and so on. Against each part of the operation is recorded any difficulty encountered, suggestions for re-design if necessary and also, special tools or techniques required.

The record sheets are first used for design discussion, to provide the basis for the maintenance schedules, information for planning and/or ordering tools, and so on, and then are kept as part of the basic development data against the time when trouble arises.

PART V—CONCLUSION

I have attempted to give a picture of the work of the engineer in the airline on the basis of the past eight years' experience, and have touched upon matters concerning the manufacture, operation, and financing of new civil transport equipment.

Through this paper has run the thread of the

introduction and development in service. And more new equipment will have to be made, introduced and developed in service if the position of this country in the world today is to be maintained.

It is my experience that the nature of the task, and the dependence of both the airline and the manufacturer on the skill of the airline engineer, has been insufficiently appreciated. As I have shown, the effect he can have on the economics and success of the equipment is considerable.

His work is only possible if those with whom he has to deal and on whom he depends to get the work done, understand the nature of the task and the factors which affect it.

The statement is often made that air transport is just like any other business and, in the sense that it should be self-supporting, this is true.

But in a highly competitive market with a flavour of national survival, the backbone of the job is suitable, up-to-date equipment operated safely and economically. This can only be achieved by active development in service. I have shown the technical nature of the task and the very serious way in which external influences and decisions on new equipment programmes can affect the economics.

The total cost of introducing new aircraft includes the cost of development in service. The work of introduction and development in service is as much a part of building and selling a new aircraft as the work done by the maker. It is expensive. We have shown that we can do the job technically but need the finance to cover it.

Many can produce project designs for new civil aircraft, few can undertake with success the total engineering needed to produce a first class job. Continuity of experience and a strong manufacturer/operator liaison is essential.

We have a very small number of engineers in this country with operating experience who are in a position to transmit this to the manufacturer. We must therefore concentrate the maximum effort on the smallest possible number of new types and not spread the limited skilled effort available over too many. Only by so doing can we produce aircraft which will succeed in our own airlines and in the export markets.

ACKNOWLEDGMENTS

I should like to acknowledge first the loyalty and support I have received over this whole period from the Project and Development staff of B.E.A., without whose continued efforts and recent assistance this paper would not have been written; also, the many friends within B.E.A. and outside who have helped so much during the years and tried to understand our problems.

I should like also to acknowledge the help and assistance I have always received from engineers in the Industry and in other airlines on both sides of the Atlantic. My thanks are due, too, for permission from the Society of Automotive Engineers to reproduce the table showing sources of introduction costs from my lecture " Introduction of New Aircraft."

Finally, I should like to thank British European Airways for permission to give this paper, the views expressed therein being entirely my own.

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APPENDIX I

BRITISH EUROPEAN AIRWAYS.

PROJECT AND DEVELOPMENT BRANCH.

ELIZABETHAN AIRCRAFT.

SUMMARY OF ENGINEERING SERVICE DELAYS FOR NOVEMBER 1953.

No. of scheduled Elizabethan departures	1,158
No. of engineering delays and concellations	102

DETAILS

Miscellaneous Causes

Awaiting serviceable aircraft	6	
Confusion between IRV Lever and AI Isolation lever	1	
Positioning	1	
U/C ground locks left in	1	
Hit birds	1	
		10

Airframe

Play in flying controls. Damper pads and torque tube changed	1
Brake feed pipe assembly changed	1
U/C door rod changed	1
Brake spider changed	1
Toilet door changed	1
Emergency window dislodged	1
Low hydraulic air pressure	1
Rudder hinged door fouling shroud—rectification deferred	1
Hydraulic air charging valve leaking—tightened	1

Ailerons heavy—no fault found	1
U/C door damaged—rectification deferred	1
Blower hose burst—rectified	1
Brake leak—rectification deferred	1
Windscreen cracked—referred to base	1
Checking tailplane spar	1
Brake piston assembly changed	1
Brake seals changed	1
Pressurisation ducting repaired	1
Miscellaneous minor snags	1
Passenger window changed	1
Brake pads changed	1
Wing tip and aileron changed (damaged)	1
	—— 22

Electrical

Unidentified electrical defect	1
Bad starting—connection remade	1
U/C not retracting—fault in feed from TB 15 to Relay 15—rectification deferred	1
AI pressure switch changed	1
Oil temperature gauge changed	2
Tail navigation light bulb changed	1
Comb. heater temperature gauge changed	1
No heat switch changed	1
Voltage trimmer changed	1
CHT thermo couple changed	1
AI actuator changed	1
CHT gauge changed	1
Landing lamp changed	1
Press, to test connection remade	1
Emergency battery check, after discovering that wire locking of battery switch had become dislodged	1
Gyro unit changed	1
Fuel pressure warning light on—no fault found	1
Batteries changed	1
Navigation light u/s—rectified	1
Alternators off balance	3
Inverter changed	2
Inverter brushes cleaned	3
External power supply fuse changed	1
Hydraulic pump circuit breaker changed	1
Oil pressure transmitter changed	1
	—— 31

Radio

AD 94 receiver changed	1
ADF receiver changed	2
MF aerial changed	1
Unidentified radio snag	1
	—— 5

Power Plant

Plugs changed	17
Gear box drive coupling changed	3
Mag drop—no fault found	1
Carburettor air inoperative—no fault found	1
Engine changed—fire in	1
RPM lever stuck	1
Cutting—no fault found	1
Difficulty in replacing spinner	2
Fluctuating oil pressure—no fault found	1
Bad starting—LT booster coil used	2
Bad starting—started with Comet starting unit	1
Oil pressure relief valve cleaned	1
	—— 32

APPENDIX II

ELIZABETHAN AIRCRAFT.

SUMMARY OF ENGINEERING SERVICE DELAYS JULY-DECEMBER 1953.

Total No. of Scheduled Departures	7,412
Total No. of Engineering Delays	676

Miscellaneous Causes

Lack of serviceable aircraft	75
Starting trouble	10
Refuelling	9
Seat conversion	2
A/C damaged	6
Loss of aircraft documents	2
Awaiting aircraft documents	1
Toilet cleaning	2
Re-oiling	1
Captains' technical query	2
Toilet spillage on tarmac	1
Emergency window opened	2
Confusion between Inward Relief Valve lever and AI Isolation lever	1
Positioning or tarmac congestion	3
U/C ground locks left in	1
Hit birds	1
Lack of headrest covers	1
De-frosting	1

Airframe

Multiple minor defects	10
Difficulty in fixing seat	1
Tail oscillation—no fault found	1
Vibration—tail unit fabric refitted or removed	7
Directional flutter—rectification deferred	1
Trimmers freezing	1
Aileron trim snag rectified	5
Aileron drum unit change	1
Slackness in control cable	2
Elevator control defect	1
Rudder cable drum stop binding	1
Rudder pedal adjustment rectified	1
Control lock tape change	1
Rudder hinged door fouling shroud	1
Checking tailplane spar	2
Brake spider change	7
Brake assembly change	3
Brake assembly rectified	9
Brake pipe repaired	2
Tyre valve changed	1
Tyre changed	10
Wheel hub nut change	1
Oleo charging valve rectified	1
N/W locking plunger change	1
Main oleo change	1
U/C door rod sheared	7
U/C uplock change	1
U/C door damaged	2
Sliding window change	1
Sliding window stop change	2
Windscreen change	4
Passenger window change	1
Window surround repaired	1
Toilet u/s—rectified	1
Toilet plunger stuck	1
Toilet cap change	1
Toilet door change	1

Toilet drain seized	2
Galley waste pipe repaired	1
Smell in aircraft	1
Hydraulic charging valve tightened	1
Low hydraulic pressure	2
Steering control valve change	3
Steering jack change	1
Hydraulic pipe change	4
Hydraulic leak—deferred	2
Hydraulic pipe repaired	1
Windscreen wiper bled	11
Windscreen wiper blade adjusted	3
Windscreen wiper leaking	1
Windscreen wiper pin changed	1
Door lock u/s—rectified	6
Air lock in water system	1
Cowling lock attachment bracket change	1
Door seal valve freed	1
Door seal change	1
Door seal bottle low	1
Pressure reducing valve u/s	1
Spill valve not closing	1
Blower outlet pipe	5
Pressurisation duct blank missing	1
Fire extinguisher change	1

Power Plant

Mag drop—no fault found	1
Mag drop—cleared	1
Surging	1
Carburettor hot air inoperative—no fault found	1
Low torque—no fault found	1
Cutting, rough running—no fault found	8
High oil temperature—no fault found	1
High oil temperature—rectified	2
Propeller not going into brake	1
Metal in filter—rectification deferred	1
High oil consumption	1
Low oil pressure—no fault found	2
Low oil pressure—rectification deferred	1
High CHT—no fault found	1
Low power—no fault found	1
Plugs changed	62
HT lead change	1
Plug lead adrift	2
Distributor change	1
LT generator change	1
Bad starting—no fault found	18
Bad starting—priming system flushed	10
Bad starting—booster coil change	6
Bad starting—plugs changed	2
Bad starting—HT lead change	1
Bad starting—isolator spark gap rectified	1
Bad starting—LT booster coil used	24
Bad starting—started with Comet starter unit	1
(Further cases of bad starting under Instruments/Electrics)	
Auto coarse u/s—rectified	2
Auto coarse u/s—engine change	1
Oil filler cap adrift	1
Oil cooler change	3
Oil cooler rectified	5
Suspect cooler coring	1
Oil sump float valve sticking	1
Oil pump thrustat gagged	1
Oil scavenge line leaking	1
Surge valve change	1
Oil pressure relief valve cleaned	2
Oil sump drain cap leaking	1
CSU pinch bolt off	1
Propeller seal change	1
CSU change	3
Incorrect TO RPM	1
CSU controls stiff	2
Difficulty in fitting spinner	2
Braking pump change	1
Propeller blade repaired	1
Spinner backplate cracked	1
Exhaust shute u/s	1
Exhaust pipe change	1
Exhaust pipe adrift	1
Gear box drive change	15
Gear box drive detached	1
Air intake flap change	1
Fuel metering unit change	1
Bleed seal change	2
Boost line change	1
Fire in engine—engine changed	1
Torquemeter head change	1
Pressure refuelling cap seized—repaired	2
Throttle damper u/s	2
Cowling had to be opened to remove superfluous cowling pin	1

Instruments and Electrics

Artificial horizon change	7
ASI change	1
Turn and slip change	2
Altimeter change	1
Pitot head change	2
CL 2 amplifier change	2
CL 2 master indicator change	1
CL 2 gyro unit change	2
Hydraulic pressure gauge change	1
Hydraulic pressure gauge—rectification deferred	1
Fuel pressure Tx. change	1
Oil pressure Tx. change	1
Boost gauge change	1
Torquemeter bled	1
Auto pilot gyro platform levelled	1
Oil temperature gauge change	2
CHT gauge change	1
CHT thermo couple change	4
DI Temperature gauge change	2
Carburettor temperature bulb change	1
Carburettor temperature gauge change	1
Low torque switch change	2
AI pressure switch change	1
Fuel pressure warning switch u/s—deferred	1
No heat switch change	1
Smoke detector defect—deferred	1
Voltmeter change	1
Alternators balanced	4
Low bus-bar voltage—no fault found	1
Complete electrical failure—no fault found	1
Unidentified electrical snag	3
Fuel pressure warning light on—no fault found	1
Phase failure—no fault found	1
Phase failure—rectification deferred	1
Voltage check after battery emergency switch locking broken	2
Alternator trimmer change	2
Battery change	2
Transformer/rectifier unit change	1
Inverter change	8
Inverter rectified	6
T/R box thermal trips tripped	1
Bad starting—starter changed	4
Bad starting—priming solenoid changed	2
Bad starting—priming solenoid rectified	4
Bad starting—priming pump change	1

Bad starting—connection remade	1
(Further cases of bad starting under Power Plant)	
Priming button change	1
Miscellaneous relay changes	3
Miscellaneous relay rectified	3
Miscellaneous CB changes	8
CB tripped—no fault found	1
Plug u/s	4
Connection remade	11
Cable faulty	4
Fuse change	4
Micro switch change	1
Propeller control box change	1
Oil cooler shutter inching control u/s	1
Coarse pitch solenoid change	3
Actuator change	4
Actuator u/s	2
Hydraulic pump motor change	1
Landing lamp change	3
W/W motor change	1
Booster pump/motor change	4
Bulb change	8
Galley water heater rectified	1
Cabin temperature controller u/s	1

Radio

STR 12 Mod/PU change	5
VHF u/s—no fault found	1
VHF u/s—rectified	1
STR 12 Tx/rx change	5
STR 12 junction box change	1
VR 61 change	4
AD 94 receiver change	2
MF aerial change	1
Main aerial feeder change	1
MF drive unit change	3
MF P.A. unit change	4
HF drive unit change	2
MF Tx u/s—no fault found	1
ADF wiring fault	1
ADF receiver changed	5
ILS u/s	1
ILS CB change	1
ILS localiser/marker Rx change	3
ILS controller change	1
ILS indicator change	1
I/C transformer u/s	1
I/C station box change	1
Unidentified radio defect	2

APPENDIX III

BRITISH EUROPEAN AIRWAYS
PROJECT & DEVELOPMENT BRANCH COMPONENT LIFE RECORD

AIRCRAFT Viscount UNIT Instrument 'Y'

MONTH OF YEAR 1953

REASON FOR REMOVAL	TOTAL REMOVALS	% OF LIFE 0	10	20	30	40	50	60	70	80	90	100	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	HOURS AS % OF TOTAL HOURS
1 Low output																									
2 Low discharge																									
3 High discharge																									
4																									
5																									
6 Miscellaneous																									
TOTAL DEFECTS																									
	DEFECTS AS % OF NUMBER FITTED												DEFECT RATE PER 1000 COMPONENT HOURS (EX. DEFECTS AT NIL HOURS)												
													MONTH ‡	‡	–	‡	‡	‡	1·50	·52	1·29	·53	1·00	·42	
													YEAR ·91												
ROUTINE CHECK OR ENGINE CHANGE NOT TIME EXPIRED																									
U/S, FOUND SATISFACTORY ON TEST																									
TIME EXPIRED																									
TOTAL REMOVALS	67	2	2	6	7	9	5	9	4	3	4	16	1	1	–	2	7	11	8	11	10	7	6	3	
													APPROVED LIFE												
REMARKS													600	600	600	600	600	600	600	600	600	600	900	900	

‡ Insufficient data available.

FORM D110 D 65/76 4"

APPENDIX IV

SOURCES OF EXTRA COST DUE TO INTRODUCING NEW AIRCRAFT FLEET

(In addition to cost of aircraft and spares)

A. DIRECT COSTS

(1) Low utilisation on initial operations

On a new type of aircraft:
- *a* Caution.
- *b* Mechanical faults actually arising.
- *c* Inexperience in maintenance methods.
- *d* Undeveloped maintenance control, high % standby, etc.
- *e* If the worst comes—grounding.
- *f* Unknown factors in high altitude operations and traffic control with turbo-props.

These items may well be largely compensated for by holding obsolete types in reserve, but see A. (8) and A. (9). Would cause higher obsolescence and Insurance costs per flying hour.

(2) Extra engineering costs on new type due to:
- *a* Inexperience in maintenance methods.
- *b* Inefficient maintenance planning on a small (initial) fleet.
- *c* Shortage of materials and spares.
- *d* Detail design faults.
- *e* Modifications awaited.
- *f* LOW engine and power plant item overhaul life (caution with new type engine + lack of development).
- *g* SLOW initial power plant turnaround and engine overhaul turnaround due to inexperience with new components.

(3) Training of Engineering and Traffic staff, Tradesmen, Inspectors and Outstations Engineers. (N.B. including worktime lost.)

(4) Flying staff courses and tests—Captains', First Officers', Radio Operators', as well as Stewards' flying costs on new type plus expenses. (N.B. including worktime lost.)

(5) Increased hourly costs due to:
- *a* Small initial fleet giving poorer crew duty integration.
- *b* Low aircraft utilisation (A.1) giving low crew utilisation for a given flying staff strength.

(6) Increased fuel consumption costs if pressurisation equipment malfunctions requiring *lower* altitude operation until fully developed.

(7) Additional flying equipment spares due to initial LOW LIFE (or unknown life) of components (chiefly power plants) may increase obsolescence and Insurance costs.

(8) Continued Insurance and accommodation costs of obsolete types retained in a serviceable condition as reserves.

(9) Extra engineering maintenance and overhauls of obsolescent aircraft types retained in a serviceable condition as reserves.

B. INDIRECT COSTS

(1) Project Engineering.
- *a* Performance, weight analysis and costs.
- *b* Design liaison.
- *c* Installations, equipment, etc.

(2) Development Engineering.
- *a* Modifications.
- *b* Weight control.
- *c* Technical publications.
- *d* Development flying.

(3) Maintenance Branch.
- *a* Spares provisioning and planning.
- *b* Ratefixing costs.

(4) Special ground equipment and tools/jigs for:
- *a* Engineering workshops, etc.
- *b* Traffic, *e.g.* loading equipment, passenger motor coaches, etc., involving increased obsolescence and Insurance costs.

(5) Flight Operations analysis into flight requirements for:
- *a* Radio.
- *b* Navigation and aids.
- *c* Meteorological information. High altitude flight data especially for turbines.

(6) Commercial:
- *a* Route studies.
- *b* Traffic research.
- *c* International agreements (fares, etc.).

(7) Accounts:
Some additional clerical costs.
Budget control, etc., for an extra type.

(8) Purchasing: additional costs associated with:
- *a* Buying procedures and inventories.
- *b* Stores organisation.
- *c* Contracts for equipment.

(9) Buildings:
New accommodation (if required).
Cost of hangars, stores and removals and/or rentals of further properties.

(10) Staff expansion:
New supervisory and/or clerical staff to handle increased engineering production as well as greater traffic IF WARRANTED by new fleet.

(11) Consultants:
- *a* Legal (contracts).
- *b* Industrial designers (interiors).
- *c* Medical (high altitude effects).

C. REVENUE LOSS

(1) Low utilisation. Providing a lower revenue earning capacity. Due to reasons as A. (1). This item may well be largely compensated for by holding obsolete types in reserve, but *see* A. (8) and A. (9) which may limit number of reserve aircraft.

(2) Low load factors on initial operations dependent on the rate of build up of advertising and traffic with larger size aircraft.

(3) Deliveries from manufacturer and/or completion of B.E.A. flight development NOT synchronising with seasonal traffic. This may *not* be perfectly covered by the reserve of obsolescent types due to:
- *a* Base accommodation limitation.
- *b* Advanced booking on larger a/c capacity.
- *c* Cost of extra engineering. Economic limit to number of obsolete reserve aircraft.

(4) Best potential revenue earning routes and frequencies not discovered in the first season of operation with a new type owing to:
- *a* New commercial timings — higher speeds.
- *b* New balance with competitors operating older types.

(5) Possible reduced payload due to malfunctioning of pressurisation or other equipment requiring increased fuel loads at lower altitudes of operation and requiring hops for the longer routes.

(6) Aircraft not operating at maximum efficiency until last operating techniques and necessary fuel reserves have been determined.

NOTE. It will be seen that certain items could be excluded if costs due to increased scale of operations could be rigidly separated from those arising only from new type introduction.

Discussion

THE PRESIDENT: He was interested in Mr. Morgan's emphasis on the difficulty which they found in civil work in making up their minds in 1954 about the type and detail of all the equipment for introduction in 1959/60, and something that was going to be used until about 1970. He did not wonder that it was difficult, but it was not unique, Mr. Morgan had put in a nutshell the problem that beset most of them, particularly in military aviation, so there should be a good deal of common ground there among the audience, whichever type of aviation they happened to be interested in.

He was also most interested in Mr. Morgan's difficulty in getting what he described as "practical operating knowledge" into the manufacturer's design office, but again the Royal Air Force, if they were properly represented that evening, would probably say "Can we join with you?" They seemed, as constructors of aeroplanes, to be not too bad at building the flying machines themselves; they seemed to behave pretty well, even on Mr. Morgan's Appendix I and II. He was interested to notice that for the periods Mr. Morgan gave to the end of 1953, whether one month was taken or the six months, about a fifth of the total number of occasions on which passengers were inconvenienced were due to the things Mr. Morgan described as attributable to the aircraft itself, and on looking into the details he noticed the number of times the doors would not remain shut or open. He had had practical experience of a Stratocruiser which had to be abandoned because nobody could shut the door. It did not seem to him to be a very cheering thing, considering everything that had gone into the making of that aeroplane, but he was entirely on the side of the people who wanted to abandon it—a pressurised aeroplane whose door opened outwards and would not shut reliably was not a pleasant thing.

S. D. DAVIES (Chief Designer, A. V. Roe, *Fellow*): This was a paper based on practical experience and which undoubtedly reflected the harsh realities of life which Mr. Morgan had seen during the early years of B.E.A. He had found the paper extremely interesting as a down-to-earth account of the difficulties which faced the engineering staff of airlines in general and B.E.A. in particular. These particular difficulties seemed to be admirably summed up in a sentence in Part I of the paper which would bear repetition: "Experience of the performance and usefulness of the civil transport equipment in service has now become, not as in so many military cases, the performance of one task with the utmost efficiency at one moment in time, but the continuous execution of a complex task all day and every day to an acceptable standard of efficiency, with no possibility of a pause." He repeated that because it seemed to him to sum up why people in the Aircraft Industry might at times appear to be a little dense on the subject of serviceability. It was a different operation in this emphasis on continuous operation from most (but not all) military operations.

The paper mentioned ways in which manufacturers could ease the burden; he could take a detached view because his company did not build aeroplanes for Mr. Morgan's airline. There were many points he would like to comment on, but one major issue appeared to revolve around the question of development costs. The paper was cost conscious all the way through, as it should be. In this connection the introduction of new aircraft struck him as being the prime factor which affected the manufacturers. B.E.A., as Mr. Morgan pointed out, had doubled their difficulties by introducing two new types almost simultaneously, but even ignoring this factor Fig. 6 showed a pretty dismal tale—the operating cost at the beginning of service of a new type. It had a vertical scale which showed initial costs to be, approximately, just over three times what it settled down to at some period which he deduced from remarks made by Mr. Morgan to be about three years; in other words it had taken three years to drop down to approximately one-third of the original direct operating cost.

From the manufacturer's point of view it was important to improve this situation because clearly it was one of the biggest reasons why the airlines would not buy new equipment, and he felt that Mr. Morgan might be able to enlighten them on one or two points to see whether this situation could be improved. Appendix IV gave a fairly voluminous account of all the different kinds of ways—some of them quite unexpected to the uninitiated—in which extra costs could be involved due to introducing a new aircraft fleet, but it seemed to him that a very large proportion of those costs were in fact inevitable. The training of staffs and the provision of spares, tools and ground equipment were all necessary because a new aeroplane was introduced, and even if the new aeroplane were perfect and had no snags at all in the first year of its operating life, it was probable that the high initial peaks in Fig. 6 would not be very greatly modified, but he did not know. Perhaps Mr. Morgan could give a rough idea of the proportion which could fairly be blamed on the aircraft manufacturer if he had made an aeroplane with snags in it; the rest, of course, was to be blamed on the high policy which decided it was worth while having a new aeroplane.

If they assumed that the high initial operating costs were really due to significant mechanical troubles, had they explored all possible ways of reducing them?

For example, the flight testing of aircraft today to get a Certificate of Airworthiness inevitably involved many hundreds of hours of flying, and he would guess that that disposed of most of the airframe snags—but what it certainly would not do, was to show up the equipment snags of a secondary nature which did not affect the conduct of the manufacturer's trials. If a particular piece of apparatus did not work when perhaps a four-hour test was scheduled for stability or performance requirements, obviously the test was not held up, whereas if something major were wrong with the airframe some action was taken. He concluded that no matter now the manufacturer tried to clear his snags he

certainly would not be able to clear the secondary equipment snags without many hundreds, if not thousands, of hours of running.

He though it possible that if they could fairly say that most, or a large proportion, of the snags were of a secondary nature—although they were not secondary from the airline's point of view; they were primary because they delayed the service—then possibly more prolonged and very severe ground rig testing would go a long way towards showing them up earlier.

A possible way to do this would be to build a non-flying aeroplane, completely equipped, and subject it to ground tests rather on the lines of a ground resonance test. They could couple with that a trained crew of morons to keep opening and shutting the doors! On the face of it this would be a pretty expensive business, and he did not doubt that the first cost of this non-flying aeroplane would be pretty nearly equal to that of a prototype, but on the other hand it might eliminate some of the service delays and consequent airline test flying which cost the money.

A non-flying aeroplane whose cost was comparable with the prototype might sound rather horrifying, but it would at any rate absorb the cost of the mock-up and modern experience showed how accurate mock-ups must be; they were in fact getting as elaborate as the aircraft. He called it a non-flying aeroplane with a deliberate purpose: if it were called a mock-up people in the design office and the shops would not make it right, but if it were called an aeroplane it stood a reasonable chance of being made to the design which was intended to be flown in service!

It was obvious that, met early enough and treated properly, many of the problems of accessibility and replaceability would be dealt with more expeditiously than they were now. Very elaborate servicing teams were being built up and they liked to get hold of the prototype to carry out their dismemberments, but the prototype was there to fly, not to be taken to pieces. The non-flying aeroplane on the other hand would be ideal for the purpose of such servicing checking.

In Part III Mr. Morgan said "Civil and military requirements are so dissimilar (in some fields the divergence between the two is even increasing) that the development of civil transport aircraft from military designs is not generally likely to produce the best civil aircraft." He seemed to have heard that before: it was a pretty hardy annual but it was not necessarily correct. He thought it was always said in a manner that conjured up a vision of a bomber being converted into a poor transport, but surely that was not what was meant. It was possible to visualise a situation where successful civil aircraft could be based on the aerodynamic and structural design of a military aircraft, and many of the desirable characteristics of civil transport from the maintenance and servicing point of view were just as equally desirable and as essential in the military field. This possible solution should not be too lightly dismissed, because it did provide a means of carrying much of the very heavy development costs of the new aeroplane, and possibly some of the tooling costs. One could almost write a paper in itself about this particular topic, but in view of the author's clear exposition of the finanical consequences to an airline of introducing absolutely new equipment the alternative of developing an existing military type should not be ignored.

Another point that should be borne in mind: when a manufacturer got involved in developing a brand new four-engined civil aircraft he was taking on a major undertaking which could lock up a high proportion of the design staff and research facilities for anything up to five years before production could be started. In fact it was such a major undertaking that it was unlikely that a prototype would be started without the guarantee of respectable production orders. He meant, of course, a brand new aeroplane from a blank piece of paper, and not a development from a military aircraft. He would like to emphasise also that this question of being reluctant just to build a prototype was not merely on the ground of covering the prototype costs because those could well be covered by Government order; it was much more that the manufacturer tied up his design and research staff for a period of five years and at the end of it he might have a very successful and interesting prototype but an empty shop with no production orders. It seemed to him most unlikely in the future that anybody was going to build a prototype civil aeroplane unless those who had ordered that prototype had sufficient faith in the manufacturer to place a reasonable production order from the word "Go"; and with the time scale Mr. Morgan talked about he would guess that the non-flying prototype would be a very small expense in the total cost of the project.

There were one or two points of detail in the paper from which all might take lessons to heart. In fact he was very struck by the parallel between manufacturing aeroplanes and running them, and he would like to try the effect of using the Request for Modification form in Fig. 3 in his own organisation; if they could not find a use for such a document he would be most surprised!

Copies of the "Nine points for detail designers" should be printed and distributed, not only in Design Offices to design civil aeroplanes but to design decent aeroplanes! On point 5 concerning interchangeability the paper said:—"To the operator it simply means that a part or component can be taken off one aircraft and put straight on to another with no drilling, reaming, filing or other wangling." But what was a "part"? There must be a limit. He assumed it meant something put on with a screwdriver or a spanner.

If the designer were backed up by a reputable works organisation three-quarters of the points on interchangeability and accessibility and replaceability were being dealt with all the time. They did feel that aircraft draughtsmen should be very alive to that point, and if they were not, the works would soon draw their attention to it because they would suffer just as much as the operator afterwards: and how he agreed with the section about cleanliness!

As an example of what he called the "down-to-earth" technique in this paper he was grateful for at last having heard a logical explanation of why tools should not be used to operate access doors for servicing. It was so true and yet all of them who were engaged in

the design of aircraft with air speeds continually rising were, of course, completely allergic to the idea of easily openable doors; they knew they were a hazard at high speed and they all wanted to see that they were well and truly screwed down. They had all heard before that ". . . . those jobs must be done in the open under all weather conditions . . . ." but they recognised sordid reality when they heard that ". . . . such operations for example, toilet and domestic water servicing, are done by unskilled operators, who, by union rules, are not allowed to wield even set spanners. If any sort of tool is necessary a tradesman must be called in." Now nobody in a design office would ever have given that a moment's thought. If that were true, it was a pity somebody did not say so before—they would not have been half as unreasonable!

B. S. SHENSTONE (Chief Engineer, British European Airways, *Fellow*): He would like to say one or two words about the difficulty of deciding which defect to go after, there being so many. They could do what Mr. Morgan suggested, that was make an analysis and find out if a defect occurred often enough and caused sufficient delays then, if it did it was the defect they were after: however, everybody in the world was not so analytical as Mr. Morgan, and some people said "Defects? Oh, the way to find them is to go to the man on the job—he will tell you." Well, that had been tried and the man on the job had listed the defects, but they found that all he listed were the defects he had met in the last two days, and they might have been good or bad days and really they were not the defects that mattered at all.

The other way was to listen to what you were told. Somebody would come roaring in and say "If so-and-so is not done we will not fly it any more," or "If so-and-so is not done something else will happen," and that, of course, was a method which was extremely difficult to resist. It all depended on who said it—they must bear that in mind—and really the best way to do it was the way Mr. Morgan suggested, plus just a little give away to certain people who wanted something done regardless.

The only other thing he would like to congratulate Mr. Morgan on was for delivering a technical paper without getting into politics. They knew it was very easy to speak politically without becoming technical—that they heard every day—but curiously enough it had become rather difficult to speak technically without being political. In fact he did not know how Mr. Morgan did it: possibly he had learned from the experience of others!

B. P. LAIGHT (*Associate Fellow*): He thought that manufacturers were giving rather more attention to some of the points that Mr. Morgan had mentioned than would be inferred from the paper. He rather felt that Mr. Davies avoided the subject but he would like to explain some of the problems which were involved in this work of designing aircraft to have a long life. That was really the need behind Mr. Morgan's requests for things that worked. If they worked properly, and continued to work, a lot of his paper would be unnecessary.

He thought that the basic difficulty with an aeroplane was that the manufacturer could not test it for long enough to establish the true lives and reliability of components. His testing on one aeroplane would be limited to between 500 and 1,000 hours and this would reveal all the larger troubles, which would be put right, but it did not truly indicate the performance that would be obtained in airline service.

Considerations of time and expense limited the flying that the manufacturer would do and he would have thought that a reasonable balance had been achieved between development by the manufacturer and by the operator. The behaviour of an aircraft in service, depending as it did on the operator's treatment of it, could never be inferred by manufacturers' tests alone. He was struck by the astronomical figure of one million pounds given as the cost of being the first operator of a new aeroplane. This suggested that there might be some reduction in overall cost if one of the operators' aeroplanes were flown along his routes for some thousands of hours, without doing any useful transportation but only for test purposes to establish lives and reliability of components. This would avoid the difficulty of trying to combine airline development work with airline service.

He would be interested to know how Mr. Morgan at present arrived at the lives of the parts of his aircraft. Starting from prototype parts, it often happened that after considerable technical discussion and testing of a particular piece to go in an aeroplane, the manufacturer of that particular part came to the aircraft designer and said that it could only be used for, say, 20 hours and after that it must come out of the aeroplane and go back for stripping. Mr. Morgan would probably like a life something in the region of 2,000 hours, and that was quite a jump from some initial small figure. Perhaps the aircraft designer needed to be tougher with the man who had supplied things for the aeroplane and should insist that it did not go in until the supplier was willing to trust it for quite a long time.

Another matter which came up after a lot of flying time was structural fatigue. He did not know if Mr. Morgan were concerned with that but there again one had a very sticky problem which could be tackled—and, of course, was tackled—by a lot of bench work, and he thought all manufacturers of civil aeroplanes were very alive to the fatigue problem and did all they could. Unfortunately the state of affairs was such at present that one could not be one hundred per cent certain that the aeroplane would go on for the figure so often mentioned, something in the region of thirty thousand hours. Again it came back to the fact that the manufacturer himself had not done it. He personally had a liking for having done a thing if he had to say that the thing was possible. He would like to know how Mr. Morgan dealt with that.

Technical people had an interesting time in attempting to be financiers, and adding up the value of improvements in aeroplanes. There were some rather interesting figures in Mr. Morgan's chart and he thought that the

value assigned to $\frac{1}{8}$ of a pound of weight was rather striking. He did not know how often the money value assigned to modification would really be of significance in deciding whether it was done or not, but if $\frac{1}{8}$ of a pound of weight was really worth as much as was indicated, aircraft designers should take very serious note of it. The question often arose whether it was worth doing an elaborate test of a particular part of an aeroplane in the expectation that having done it, some small amount of weight reduction could be made. He thought Mr. Morgan's figure was that one pound in weight was worth about 260 pounds sterling in the life of one aeroplane, and if there were 100 aeroplanes of the same type it would appear that some very large figure might be justifiable to save one pound in weight. Was the manufacturer really doing the right thing if he did such sums in his design office and increased the first cost of the aeroplane accordingly?

B. H. SLATTER (Armstrong Siddeley Motors Ltd.): He had found the lecture refreshing because of its emphasis on the completion of development, especially so perhaps to those who were mainly concerned with the military field. In the military field, all too often, if an aeroplane or its engine ever reached the stage where it was considered fully developed, it was also considered to be obsolete.

The remarkably fine method for deciding whether or not to introduce a modification looked delightfully simple, but he felt that the lecturer must have grossly over-simplified the problem. For example, quite frequently a modification must involve safety: how could the value of safety be assessed in commercial terms? Again, in the aero-engine development business they had perhaps a problem in that a particular component failed on rare occasions during development and they rushed off and invented a solution to it, full of confidence; but, on introducing it, they discovered they had run straight into another problem which was lurking round the corner. How could you be so sure your modification was going to work without testing it and getting a considerable amount of background on it?

Mr. Davies suggested that the enormous losses involved in the introduction of a new aircraft could perhaps be met by building a non-flying aeroplane, but he doubted whether an aircraft that never left the ground would be very convincing. He would suggest that the gap between the flying done by the manufacturer and that done in airline service might be met if, say, one of the aircraft of a new type were set aside for experimental work. It might be used for freight during that period, but all modifications could be tried out on that particular aircraft and it might be possible to test equipment which was to be introduced on future aircraft. Would it be possible in that way to save some of the enormous sum of money involved in introducing a new aircraft?

N. E. ROWE (Technical Director, Blackburn and General Aircraft Ltd., *Fellow*): As Chairman of the Branches Committee might he say how much they appreciated at headquarters what was being done in Chester and how heartily they would like to congratulate the officers and members of this Branch on such a first-rate organisation and turn-out that evening. One knew after some years' experience, what a tremendous amount of work was entailed for the Secretaries and Committees and Chairmen of the Branches, and how much individual enthusiasm counted in making things of this sort "go," and he thought the Society as a whole owed a great debt to such men for the work they did, and it was a great pleasure to be able to say so publicly and to offer one's congratulations.

These main lectures had been going on now for some years. He thought they owed it very largely to Mr. D. C. Smith, who first made the suggestion that was put before the Council, that they should have four lectures a year out in the so-called provinces—some of which were much older than London, historically—and the Council thought that was much too much and they were reduced to two. Some years later they were extended to three, and last year it was agreed that there should be four. He thought it did a great deal of good: it gave an opportunity for the Society to come out to the Branches and for the President to preside, which was always a splendid thing in the Branches, and it also gave an opportunity to the Branches to have a discussion and to have an occasion.

He thought Mr. Morgan's paper epitomised in the most direct and sincere way the practical experience of a very practical man who also had a power of analysis, which had been referred to by Mr. Shenstone.

With Mr. Davies and the President he would take up the question of the discrimination between military and civil practice. He would say that for the national benefit, if they liked, it was as important that they should have this general matter of engineering for serviceability attended to in military aircraft as it was in civil aircraft. He thought the R.A.F. would say that one of their great difficulties now was man-power: the number of men required on the ground to keep aircraft serviceable and flying and the difficulties therein because things went wrong, and particularly because things failed in a random manner.

He thought, too, that the flying services generally would echo Mr. Morgan's plea for the recognition of what he called the "airline engineer." They really had all recognised such a man for a long time but he had never seen his place in life so clearly defined as it was in this paper, and he thought the same sort of engineer was really operating in the Services and he could, with advantage, come into the picture in relation to the manufacturer, in exactly the way Mr. Morgan suggested the airline engineer should come into the picture with the manufacturer of civil aeroplanes. He thought, therefore, although it might seem that the military aeroplane was only wanted at its peak of efficiency at a point in time, to use Mr. Morgan's expression, that efficiency could clearly be developed only in peace time; in order to get that efficiency, the aeroplanes must fly and must be serviceable and must do that with minimum manpower. All the points made emphasising the need for proper design and proper attention to maintenance, and so on, for civil aircraft, he would say applied equally

to military aircraft, and he would be glad to hear what Mr. Morgan had to say about that.

When he was with B.E.A. he was much impressed by what he called the random failure, because it seemed to him it was that which led to gross dis-economy. Things were expected to go on for a certain life and they did not, and the aircraft you expected to be able to carry passengers was not there, which meant you had to have more aeroplanes than you otherwise would to do the job and therefore the aircraft could not be used as economically as they otherwise would. It also meant, incidentally, that you probably ordered the wrong spares because you thought things would have a certain life and they had not. It seemed to him there ought to be a way of doing more things on the ground, as Mr. Davies suggested.

He had talked to many people about this because he thought a laboratory experiment ought to be tried which would tell them something about what they regarded as the factors affecting life and how they would agree with actual practice. He was able while in B.E.A. to obtain from the Ministry of Supply a contract for this purpose. They took bits and pieces from the Elizabethan and had a laboratory set-up into which they fed what they regarded as the vital factors, namely vibration, moisture, dust and variation in temperature. They thought all those were probably responsible for failures of equipment in service and that if they fed them in, in the way in which they occurred in flight, then they ought to get somewhere; they took a sample flight of the Elizabethan on the B.E.A. routes to give the time cycle of the tests. That work had been going on, had now built up to about two thousand hours and he thought was beginning to show interesting results. He thought the method was one which would not necessarily be guaranteed to produce results but it was the sort of thing they ought to do more of because the alternative of development in flight was an expensive business. As brought up by Mr. Davies and as Mr. Morgan made so clear in his paper, it was expensive for the manufacturer and for the airline operator, or any operator of an aeroplane, and he thought they ought to attempt very seriously to get something going on the ground using a method and technique which would simulate flight from which results would be obtained which were otherwise obtained only in flight. He very much agreed with Mr. Laight when he said that the manufacturers of aeroplanes ought to state very clearly to those who were going to supply them with equipment, the conditions which the equipment must stand up to in terms of factors which really affected life. He suggested that they were factors of the nature he had outlined, and the manufacturer should attempt to give those factors as early as he could in the design of the aircraft. Otherwise he agreed very much with what had been said by other speakers.

C. B. V. NEILSON (Technical Director, Electro-Hydraulics Ltd., *Associate Fellow*): Having been responsible for the design of some equipment on an aircraft going into regular civil airline service he could confirm what speakers had said, quite definitely, that they did not, at the time of designing it, know anything like enough about it. After this particular equipment had been in service for a short time all sorts of troubles developed and they had to get down to it in the design office and laboratories and find solutions. In introducing those solutions they put a working party on the job to take the aircraft as soon as it came out of service and overhaul all the hydraulic equipment and put it straight back into service without delaying the regular schedule. In the course of this work they hoped that, as designers, they had learned quite a lot, but the Corporation which Mr. Morgan represented had used two types of aircraft from the same designer and perhaps he could tell them whether or not designers did learn.

He thought Sir William was taking some pride in the fact that only one-fifth of the troubles experienced in the Elizabethan were the aircraft designer's troubles. On behalf of designers of components he would like to say that one aircraft designer quite recently told him that only one-fifth of the aircraft they designed was actually designed and manufactured by the aircraft constructors themselves!

W. SKELLON: After hearing the last few remarks it looked as if the customer were always right; he would refer to one item in Fig. 7, which referred to the use of split pins; this was only a trivial detail, but to replace a split pin probably costing half-a-crown each was one occasion on which he did not think the customer was right, and he would like to know what liaison existed between the operator, the manufacturer and the A.I.D.

H. B. CUNDALL (Development Engineer, Hunting-Clan Air Transport, *Associate Fellow*): Mr. Morgan had mentioned the long life of components. There were three points about this: the first was that the components seemed to last much better if they were left alone, which was a very good reason for getting long life components and then not touching them while they were on. The second point followed—surely they should try to utilise that life to the full? He believed it was true to say that B.E.A. used a system whereby they took a component off at the check regardless of whether or not it had reached the end of its economic life. Thirdly, did Mr. Morgan think as much as possible had been done to get the lives increased of engines, propellers, and components generally, and to push them up as much as they could? Was the present system the best that they could achieve?

A. J. SMAILL (Maintenance and Overhaul Superintendent, National Airways Corporation, New Zealand) *contributed*:—One point not dealt with which was a matter of interest to airlines was the tendency for a drop in the standard of maintenance and the amount of attention given to existing types of aircraft in an airline fleet when new aircraft were taken on. The new aircraft obviously had a disproportionate amount of attention both from hangar staff and senior personnel, and existing type aircraft consequently suffered.

He would be interested to know in a little more detail the method used by B.E.A. in assessing the

necessity for modifications to aircraft in the cases where the result was rather more intangible. The type of modification he had in mind was such a thing as installing cooling fans in the cabin for the greater comfort of the passengers, or perhaps putting additional soundproofing in the cockpit to make things quieter for the crew. Those modifications could not be assessed in terms of saving of maintenance, increasing freight in payload or on other economic grounds and could be the subject of disagreement between the Operations Section and the Engineering Section. The lecture did not make it clear what representation on modifications was given to Sections other than Engineering. In airline operation this was important because it was sometimes hard for an engineer striving to increase efficiency of aircraft on a payload or operational point of view to have to accept modifications which made for an apparent loss in those directions.

Mr. Morgan's Reply

He seemed to have started something! He found Mr. Davies the most difficult to answer because he was not quite sure how much Mr. Davies agreed with him. First, on the high cost of introduction, which was a thread running through almost all the contributions to the discussion, and ways of reducing it: he still came back to the point of designing for the purpose in the first place and this entailed knowing the purpose. Nowadays he frequently flushed when he remembered some of the things he designed himself on the drawing board, with very little idea as to what was going to be done with them, what they were for, or what relation they had with something else.

One apparently trivial point he mentioned in the lecture was the subject of manuals; they should display the knowledge of how the equipment had been designed, what it was to be used for, and so on, right at the outset. The importance of the manuals in cutting down these high introduction costs could not be over-stressed. They needed to have the information in the manuals not in the form of descriptions from the designer's point of view but in the form of the reflection of what the designer knew of the operator's needs when he designed the piece.

He was afraid he could not give off-hand the relative figures for the high costs of introduction due to the equipment itself and training costs. He could only say that the high engineering costs of the equipment were bound up with the things he had mentioned in the paper, and particularly the lives of components and between operations, the amount of work on the maintenance schedule, and so on.

On the subject of proving and rig testing by the manufacturer, his own view there was one of compromise. He could see, and they had seen from the rig tests which Mr. Rowe mentioned, that there was a great advantage to be obtained from ground testing of equipment in advance. One of the snags was that it had to be done quickly. It took quite a long time to build up hours on the ground rig and one of the catches, of course, was that if they started a test with the ground rig on a certain component mounted in the way in which it was mounted in the aircraft, it must not be altered. The difficulty was that they were testing what was in effect a prototype piece of equipment and the moment they introduced a modification they were liable to unrepresentative results. Personally he did not agree with Mr. Davies' view that a full-scale ground aeroplane would be the answer. He mentioned in the paper the proving flying aspect, and there he did believe that a very great deal could be done although the number of hours was short. He mentioned the two hundred hours proving flying done on the Viscount and on the Elizabethan. In 1946 he himself put up a paper giving the figure required as one thousand hours, realising, of course, that the expense would increase the cost of the whole new fleet. He would say some figure of two hundred hours plus was needed as pure proving flying in addition to all prototype flying and the paper showed the way in which the tests should be conducted. Provided that the tests were run very strictly simulating airline conditions a tremendous amount could be learned from them.

He thought Mr. Davies said "interchangeability of what?" Well, of course, that was one of the problems. In the production of civil aircraft the manufacturer only wanted to provide in the contract for interchangeability of a small number of very large components, but the airline had to have interchangeability on a much larger number of components. It was a matter of compromise and he thought they would find, if they threshed the thing out, that his view of what should be interchangeable, would not extend much farther than Mr. Davies except that he would want more things removed with a spanner!

Overhaul lives—how did they judge how long—and he thought there was another point; was the present system of life increase satisfactory? He would say it was. He gave some detail in the paper and referred to previous papers by Mr. Hardingham and by Tye and Cundall, showing how the approach to component life increase in this country had changed since the War. On engines, for example, they had been able, in the two new engines which they had in these aircraft, to set out a programme of life development when first taking over the aircraft which startled everyone concerned, but it was interesting that with assistance from the manufacturers that programme had been adhered to. They had in fact reached, on the basis of the flying hours done so far in each aircraft, the target overhaul lives for those two engines.

The point about throwing away lives on checks was one they argued about a great deal in the airline. It was subject to economic examination. The difficulty, of course, was to keep the work down on the maintenance cycle: the major checks had to be spread as far apart as possible and a thousand hours was the sort of figure for the largest of the major checks, and it was tricky to

get a component to go in steps of a thousand hours. They were trying, as they went along, to tighten up on the amount of life thrown away on components but they were quite certain that where components did run oddly and out of phase, depending on the overhaul cost of the particular component—some were cheap to overhaul and some expensive—it was worth throwing away overhaul lives to keep the aircraft flying most of its time and to adhere to the maintenance cycle, but it was quite a tricky problem.

Did designers learn? Well, of all the things to ask him! He would say "Yes," quite definitely; that was why he stressed in the lecture the need for continuity of experience. The design staff they had dealt with, not only on aircraft but on component parts and equipment, had shown that.

On the question of civil and military aircraft, while he agreed with the speakers who said that many of the things mentioned in the paper, such as ease of servicing, should be applied to military aircraft there was still one difference, and that was that even while military aircraft had to remain serviceable for peacetime use, the number of hours such military aircraft flew was very small, so that there was a difference as between the short life and the long life operation, and he was sure that made a difference in the application of the sort of things mentioned in the paper and the need for more emphasis on the civil aircraft in certain ways, particularly as regards economics, and means of getting the long life between the various periods he mentioned. A military aircraft could be kept serviceable in peacetime with lower hours between maintenance operations than they wanted to apply for economic reasons to the civil aircraft.

With regard to modifications, he still believed that there was a price you could pay, like coming in the end to scrap the aircraft. The testing of modifications, which was a point raised by one speaker, was a very difficult problem for the airline. One of their most difficult problems was the putting in of trial installations without disturbing the operation routine of the fleet; getting the right answer and then getting the modifications in.

As regards fatigue, when buying new aircraft they would, of course, like a contract for an aircraft which, on major components, would give a fatigue life of a suitable figure, such as thirty thousand hours, and a good deal of work had gone on in that respect. Mr. Shenstone, he thought, had been doing some on a Committee of the Royal Aeronautical Society on the subject, particularly in regard to design which could help the operator with fatigue, but one could start another lecture on that subject.

Written reply:—The evaluation of certain kinds of modifications was admittedly difficult. However, their experience had been that since the introduction of the Modification Request Form with its financial estimate, the number of modifications not concerned with safety, reliability and operating economy had been very considerably reduced.

The remarks made in the discussion showed the interest in the vital question of component lives. While it was obviously desirable that military aircraft possess qualities called for on civil aircraft, such as ease of maintenance and reliability, the approach towards component lives, and running time between operations, must remain different because of the great disparity of hours run in a given time. Their philosophy in controlling this life development allowed for rapid life increase with an acceptable defect rate. This must be a matter of experience and would depend on the nature of the component itself and whether, for example, it was duplicated on the aircraft.

There was no doubt that much benefit would accrue from rig testing before the aircraft went into service and a good deal of this was done on some of the components of the new aircraft B.E.A. was now operating. But on civil work those rig tests could only form the basis for, and could not replace, the life development which must go on in service as the result of the accumulation of many hours on a large number of smaller components. It was in this important respect that civil and military aircraft must differ.

With regard to the written contribution by Mr. Smail of the National Airways Corporation, New Zealand, he did not mean to imply that when new aircraft were taken on there would be a drop in the standard of maintenance on the existing types. He did not believe that to be the case. It was inevitable, however, that during the initial life of a new aircraft it would necessarily get special attention and that must be taken into account when trying to forecast what its efficiency would be in a year or two's time.

THE PRESIDENT: He had found the paper and the discussion extremely interesting, and had been wondering whether they realised what an awful lot they were asking of an aeroplane and the bits that went to make it up. He had driven there that night in a car which he had driven himself for five years continuously—100,000 miles odd, and at a rough estimate that was equivalent to 3,000 hours. Most people considered it was on its last legs, yet it was a far less sophisticated piece of equipment than a modern aeroplane although it approximated in many ways in that it had things which went round very fast, or up and down, but it had never been rebored and it used very little oil indeed. It would probably go on for another five years, but if it did it would only have done 6,000 hours. As far as he could see in order to compare it with a modern aircraft he would have to go on driving it for fifty years, which seemed to him to be asking a lot, and it would then be regarded by the manufacturers as something worth putting in their museum.

Why did they ask so much of aeroplanes? He was not against it, of course. What would the "Queen Mary" do in hours of running if she went on for twenty years? According to his estimate it was something in the neighbourhood of 60,000. Did they really realise what they were asking of one of the most sophisticated pieces of equipment of the present time, which they used and expected to last in very much the same manner as a

motorcar. He supposed there was some reason for it; perhaps an aeroplane had an easier life, but why did it go wrong so much?

Was any branch of transport really economical? Could it really make a living in a hard world? Did the railways? Did the 'buses? He did not know but he had a strong suspicion that they would feel very uncomfortable indeed if every method of transport were eliminated by law unless it could prove that it made an actual profit, not subsidised by anybody directly or indirectly. At any rate the aeroplane did not have to ask anybody to pay for the air through which it flew. Supposing it did cost more than it brought in, was it worth it? He thought it was, hundreds of times over. For one thing they could not do without it from the point of view of defence, their mere existence, and certainly he did not think they could do without it as a means of transport both inside and outside the country, and as to the efforts of each of their airlines, whether they were the two national airlines or those magnificent independent people who were trying to make a living out of it, he was sure as a country they would get nowhere if they did not find ways and means to help them to do what they were doing even better than at present. So he was sure they would feel, with him, profoundly grateful to them, and this evening particularly to Mr. Morgan for the great trouble he had taken to compose the paper and for his skill in summarising it so well.

Compound Diesel Engines for Aircraft

by

E. E. CHATTERTON, B.Sc.(Eng.), M.I.Mech.E., F.R.Ae.S.
(Chief Engineer, Piston Engine Division, D. Napier & Son Ltd.)

The 910th Lecture to be given before the Royal Aeronautical Society was held at the Institution of Mechanical Engineers, Storey's Gate, London, S.W.1 on 22nd April 1954 and was presided over by Sir Sydney Camm, C.B.E., F.R.Ae.S., Vice-President of the Society. THE CHAIRMAN, opening the meeting, said:—

Our President, Sir William Farren, is unable to be here and has asked me to deputise. I therefore have great pleasure in introducing Mr. Chatterton. Mr. Chatteron is at present Chief Engineer, Piston Engine Division, of D. Napier & Son, and his association with Messrs. Napier dates back to 1930, when he was appointed to take charge of Experimental Design. He was subsequently appointed Assistant Chief Designer in 1938, and in 1941 was appointed Chief Development Engineer, and in this capacity was responsible for the development of the Sabre engine, which was the engine used in the Typhoon fighter.

1. Introduction

The association of a gas turbine with a piston engine is by no means a recent conception. As early as 1924 a Napier Lion Series V engine was equipped with a turbine in the manner shown in Fig. 1, the exhaust gases being fed into the turbine to provide all the power to drive the engine supercharger.

At a later date during the 1939-1945 War, many engines were installed in operational aircraft fitted with "turbo-chargers" of the type shown in Fig. 2, in which an exhaust activated turbine drives a subsidiary blower boosting the air intake of the normal engine supercharger.

While it may perhaps be said that the germ of the compounding principle is contained in these early examples, neither of them can be regarded as a true demonstration of compounding for in each case the functional conditions of the engine are normal; no attempt is made to adjust these conditions to extract maximum energy from the combination and the turbine is applied with the primary objective of extending the normal performances of the engine over a greater range of altitudes.

The extent to which this limited objective is achieved, as compared with a normal engine fitted with a two-speed mechanically-driven blower, is illustrated in the power curves of Fig. 3 which show that the engine equipped with a turbine is able to maintain a selected cruising boost pressure and therefore its cruising power, at a sensibly constant value over a wide altitude range.

This result serves to demonstrate the striking effects on engine performance which can be derived from the simplest possible association of a gas turbine with a normal piston engine.

A more recent power plant which combines a piston engine with turbines is the Curtiss Wright "Turbo-Cyclone" engine, which at the present time is installed in the Lockheed Super Constellation and other aircraft. This application differs from the two previously mentioned in that the power produced by the turbines is fed back into the crankshaft and the engine may therefore be classified as "compounded."

In this case the 18 cylinders of the four-stroke petrol engine are divided into three groups of six, each group feeding a separate turbine geared into the crankshaft system. The basic engine is the C.18.CB Cyclone to which the turbines have been added with the object of recovering as much waste energy as possible from the exhaust gases without disturbance to the established cylinder operating conditions. To avoid any material back pressure effects the turbines are therefore of the "blow-down" type, which are activated by the impulsive velocities in the exhaust ducts.

With this arrangement the power output of the 55 litre engine was increased from 2,800 b.h.p. to 3,250 b.h.p. when operating on 115/145 grade fuel, the specific weight remaining unaltered at 1·08 lb. per b.h.p. The maximum power has recently been further increased to 3,700 b.h.p. by the use of water injection. Cruising fuel consumptions of 0·380 lb. per b.h.p. per hour have been claimed for this engine under certain specified and restricted conditions of flight.

Here again it may be seen that considerable advantages are to be gained from the piston engine-turbine combination, even when the turbine is added as an auxiliary to an already developed piston engine.

If, however, a piston engine and a gas turbine are designed together in the original inception to produce a true "compound" design, much greater improvements in performance become possible, for in this case the cycle of operations can be manipulated to exploit the most valuable features of the piston engine and the turbine which can then be associated together to produce a power plant possessing strongly defined performance characteristics, which cannot be achieved by any other type of prime mover.

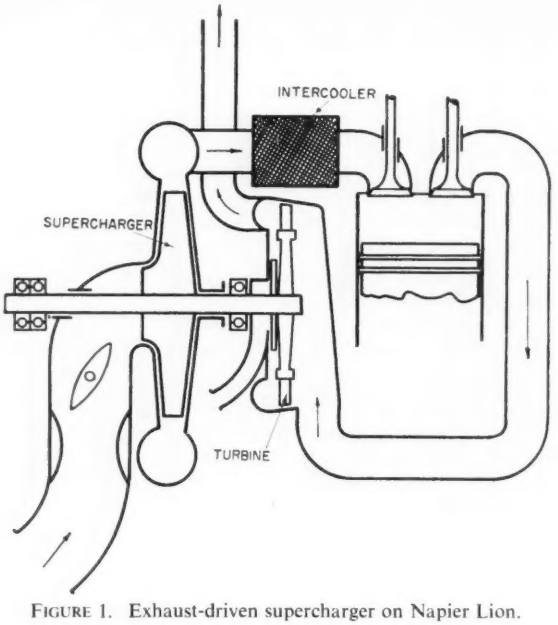


FIGURE 1. Exhaust-driven supercharger on Napier Lion.

It is the purpose of this paper to analyse the characteristics of the compound engine with particular reference to the Napier Nomad, which is the only existing example of the type and to indicate the contribution which such an engine can make in modern aviation.

2. Derivation of the Compound Cycle

If the major functional characteristics of the various types of engine are considered individually, it will be possible to indicate the factors involved in the derivation of the compound cycle and to assess the theoretical basis and practical limitations of this cycle in relation to others.

In broad terms, without too much respect for meticulous detail, the main relevant characteristics of different engines may be summarised as follows.

2.1. THE SPARK IGNITION ENGINE

The petrol burning engine, by its nature, consumes essentially all the air supplied to it and the power developed by a given size of cylinder is almost entirely dependent on the rate at which it can inhale and reject air. Apart from changes in operational speed, the air quantity can be increased by supercharging but the extent to which this is possible is limited by detonation and pre-ignition difficulties.

An approximate "indicator diagram" for this type of engine is shown in Fig. 4(*a*). Combustion takes place at constant volume and the peak temperature of the cycle will be in the region of 2,500°C. Basically the thermal efficiency of the cycle is governed by volumetric ratio V/v and this again is limited by the occurrence of detonation. Furthermore, if the supercharging pressure is increased to raise the maximum power, the compression and expansion ratios will, in general, require to be reduced to avoid detonation with consequent sacrifice in thermal efficiency over the cruising range of the engine.

It is therefore true to say that the destructive phenomenon of detonation is the limiting factor to both the power output and the thermal efficiency obtainable from this type of engine and most of the spectacular power development demonstrated during the 1939-45 War resulted directly from the introduction of fuels less prone to detonation, coupled with the use of water injection and charge coolers which allowed the charge density to be increased and its temperature reduced, thus keeping within the detonation limits.

Typical performance figures achieved from spark ignition engines in the more recent phases of their development are given in Table I.

This type of engine is not amenable to manipulation of its cycle for compounding purposes for any back pressure imposed in the exhaust system by a turbine will introduce practical difficulties, such as an increase in temperature of exhaust valves, and an increase in the mass and temperature of the residual gases which reduces the volumetric efficiency and raises the charge temperature, thus accentuating the already acute detonation difficulties. The best that can be done with this cycle is the arrangement already referred to as used in the Turbo-Cyclone in which a proportion of exhaust heat recovery is achieved without disturbance to the normal pressure and temperature levels in the engine cylinder.

Although the foregoing remarks all relate to four-stroke engines a similar situation exists if applied to the two-stroke petrol engine cycle.

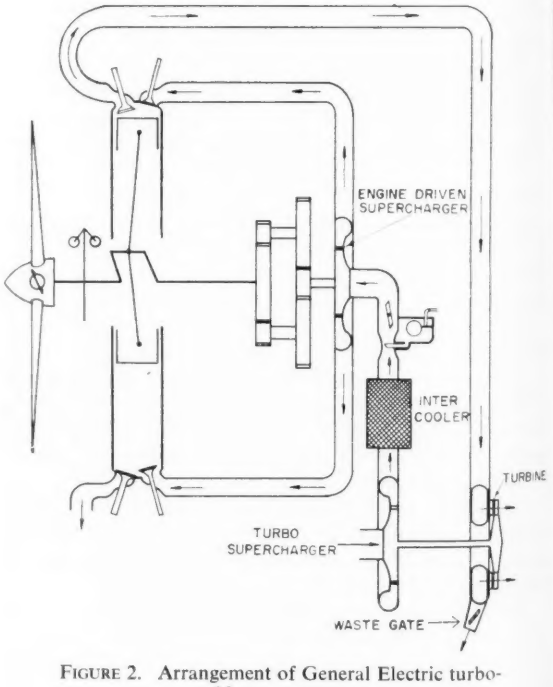


FIGURE 2. Arrangement of General Electric turbo-blower system.

2.2. THE DIESEL ENGINE

This engine also attempts to burn all the air which is supplied to it, but as in this case the mixing of fuel with the air has to take place in the cylinder within a maximum period of about 35 to 40° of crank rotation it is not found possible in practice to utilise more than about 80 per cent. of the total air trapped in the combustion chamber. For a given maximum power output the cylinder dimensions will therefore need to be larger than in the spark ignition engine. In the two-stroke Diesel engine a further loss of air occurs because of the necessity for effectively scavenging the burned gases from the cylinder, which implies a wastage of about 40 per cent. of the total air throughput which will escape from the exhaust ports or valves during the scavenging process. This air lost during scavenging is not entirely without value for it does act as an internal cooling agent and therefore reduces the thermal loadings on the pistons for a given amount of fuel burned.

As with the petrol engine, the quantity of air trapped in the engine cylinders can be increased by supercharging and, as the detonation limitation no longer exists, the degree of supercharge can be increased as dictated by the general balance of the engine design. It will be observed, however, that in the two-stroke engine any degree of supercharge can only be effective providing that a corresponding resistance, or back pressure, is offered at the exhaust ports or valves.

The approximate indicator diagram for this cycle is shown in Fig. 4(*b*). Here combustion takes place partly at constant volume and partly at constant pressure, the proportion of fuel burned at constant volume being to some extent controllable and determined by

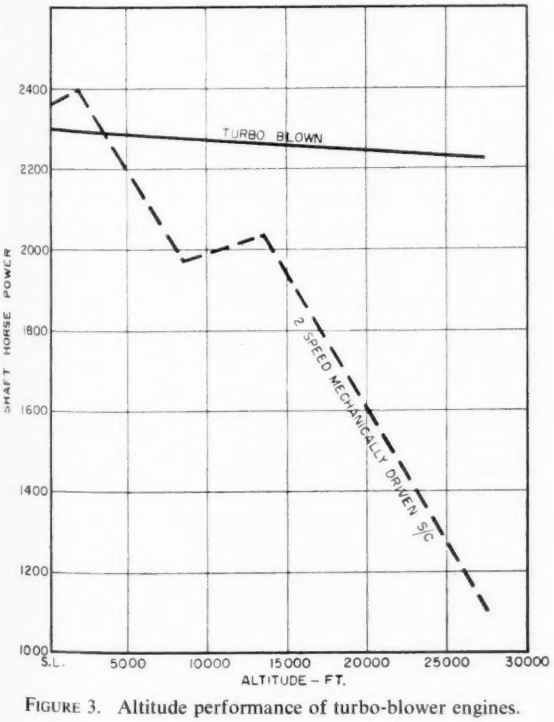


FIGURE 3. Altitude performance of turbo-blower engines.

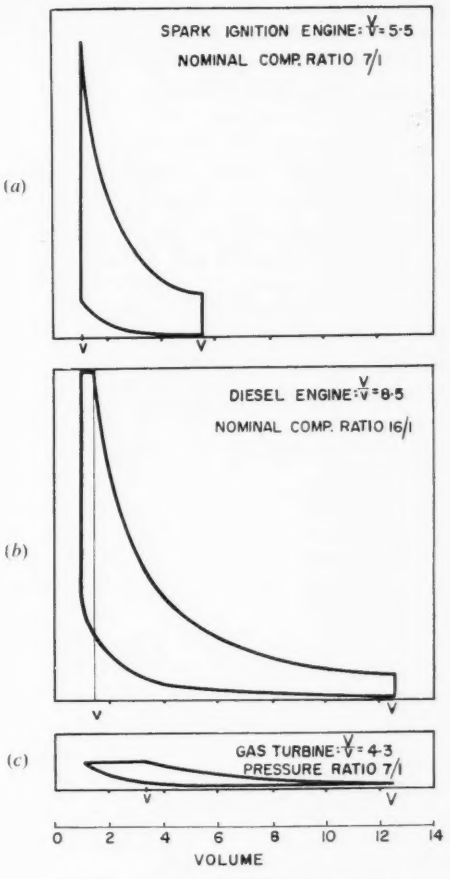


FIGURE 4. Typical Indicator Diagrams.

the limitation established by the designer for the maximum cylinder pressure.

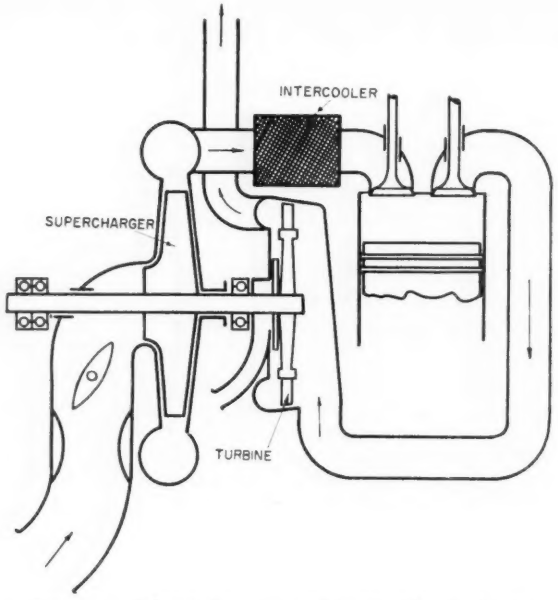
Although not strictly correct, due to the portion of constant pressure combustion, the thermal efficiency for present purposes may again be related to the expansion ratio V/v, which in this case is considerably higher than in the petrol engine case with resultant improvement in fuel consumption.

The flame temperature during combustion will also be in the region of 2,500°C. but, due to defective air utilisation, the heat of combustion is diluted to some extent and the maximum temperature spread over the total air in the combustion chamber will be reduced to about 1,800°C.

The Diesel engine has not been widely used in aviation but one engine which saw considerable service before the 1939-45 War was the Junkers Jumo engine, the results from which are also included in Table I.

It will be apparent that the cycle of operations described, particularly when referred to the two-stroke engine, is very much more adaptable for compounding purposes than the spark ignition case, for the following possible variables exist:

(*a*) In the absence of detonation or pre-ignition troubles the compression ratio and the degree of



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It is the purpose of this paper to analyse the characteristics of the compound engine with particular reference to the Napier Nomad, which is the only existing example of the type and to indicate the contribution which such an engine can make in modern aviation.

2. Derivation of the Compound Cycle

If the major functional characteristics of the various types of engine are considered individually, it will be possible to indicate the factors involved in the derivation of the compound cycle and to assess the theoretical basis and practical limitations of this cycle in relation to others.

In broad terms, without too much respect for meticulous detail, the main relevant characteristics of different engines may be summarised as follows.

2.1. THE SPARK IGNITION ENGINE

The petrol burning engine, by its nature, consumes essentially all the air supplied to it and the power developed by a given size of cylinder is almost entirely dependent on the rate at which it can inhale and reject air. Apart from changes in operational speed, the air quantity can be increased by supercharging but the extent to which this is possible is limited by detonation and pre-ignition difficulties.

An approximate "indicator diagram" for this type of engine is shown in Fig. 4(*a*). Combustion takes place at constant volume and the peak temperature of the cycle will be in the region of 2,500°C. Basically the thermal efficiency of the cycle is governed by volumetric ratio V/v and this again is limited by the occurrence of detonation. Furthermore, if the supercharging pressure is increased to raise the maximum power, the compression and expansion ratios will, in general, require to be reduced to avoid detonation with consequent sacrifices in thermal efficiency over the cruising range of the engine.

It is therefore true to say that the destructive phenomenon of detonation is the limiting factor to both the power output and the thermal efficiency obtainable from this type of engine and most of the spectacular power development demonstrated during the 1939-45 War resulted directly from the introduction of fuels less prone to detonation, coupled with the use of water injection and charge coolers which allowed the charge density to be increased and its temperature reduced, thus keeping within the detonation limits.

Typical performance figures achieved from spark ignition engines in the more recent phases of their development are given in Table I.

This type of engine is not amenable to manipulation of its cycle for compounding purposes for any back pressure imposed in the exhaust system by a turbine will introduce practical difficulties, such as an increase in temperature of exhaust valves, and an increase in the mass and temperature of the residual gases which reduces the volumetric efficiency and raises the charge temperature, thus accentuating the already acute detonation difficulties. The best that can be done with this cycle is the arrangement already referred to as used in the Turbo-Cyclone in which a proportion of exhaust heat recovery is achieved without disturbance to the normal pressure and temperature levels in the engine cylinder.

Although the foregoing remarks all relate to four-stroke engines a similar situation exists if applied to the two-stroke petrol engine cycle.

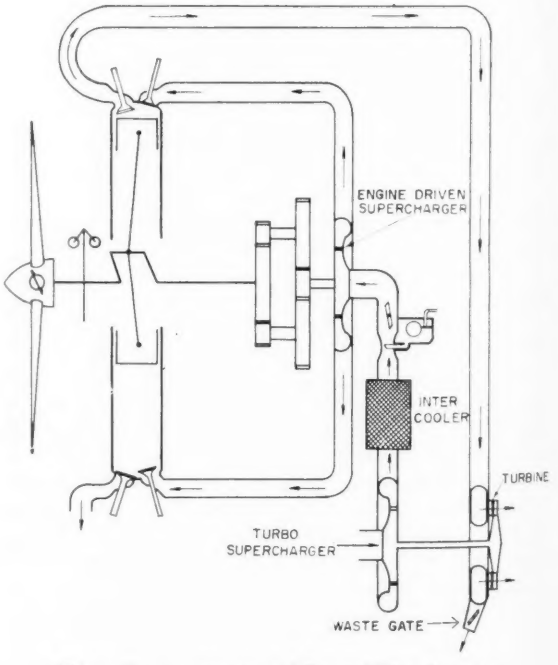

FIGURE 2. Arrangement of General Electric turbo-blower system.

2.2. THE DIESEL ENGINE

This engine also attempts to burn all the air which is supplied to it, but as in this case the mixing of fuel with the air has to take place in the cylinder within a maximum period of about 35 to 40° of crank rotation it is not found possible in practice to utilise more than about 80 per cent. of the total air trapped in the combustion chamber. For a given maximum power output the cylinder dimensions will therefore need to be larger than in the spark ignition engine. In the two-stroke Diesel engine a further loss of air occurs because of the necessity for effectively scavenging the burned gases from the cylinder, which implies a wastage of about 40 per cent. of the total air throughput which will escape from the exhaust ports or valves during the scavenging process. This air lost during scavenging is not entirely without value for it does act as an internal cooling agent and therefore reduces the thermal loadings on the pistons for a given amount of fuel burned.

As with the petrol engine, the quantity of air trapped in the engine cylinders can be increased by supercharging and, as the detonation limitation no longer exists, the degree of supercharge can be increased as dictated by the general balance of the engine design. It will be observed, however, that in the two-stroke engine any degree of supercharge can only be effective providing that a corresponding resistance, or back pressure, is offered at the exhaust ports or valves.

The approximate indicator diagram for this cycle is shown in Fig. 4(*b*). Here combustion takes place partly at constant volume and partly at constant pressure, the proportion of fuel burned at constant volume being to some extent controllable and determined by

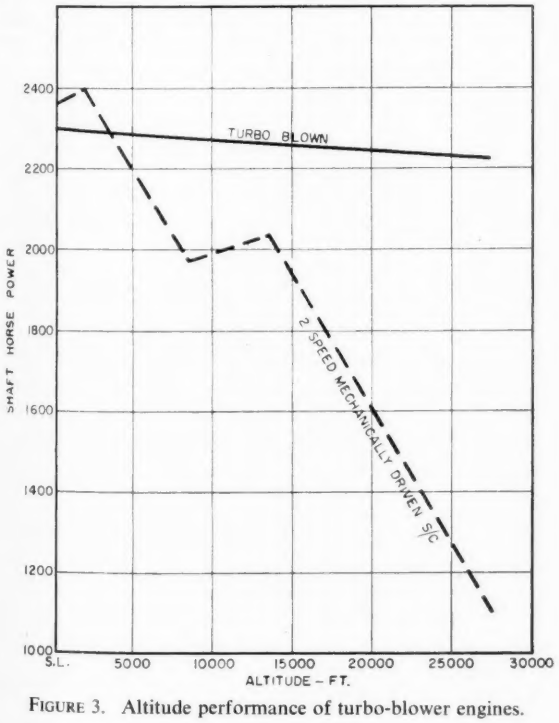

FIGURE 3. Altitude performance of turbo-blower engines.

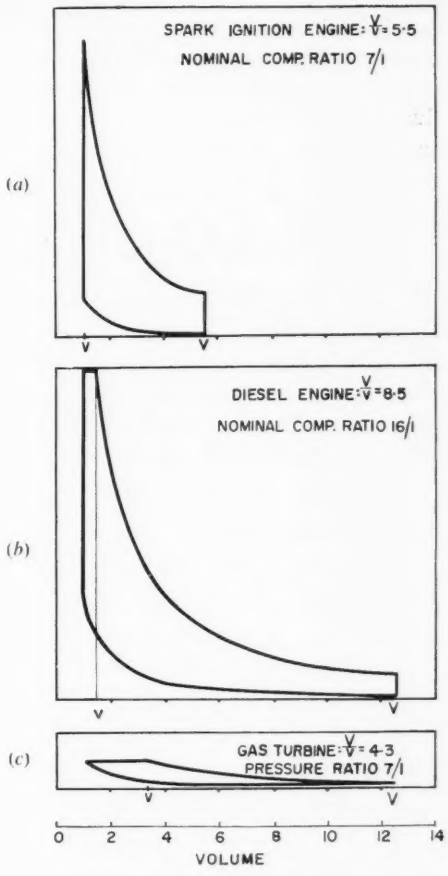

FIGURE 4. Typical Indicator Diagrams.

the limitation established by the designer for the maximum cylinder pressure.

Although not strictly correct, due to the portion of constant pressure combustion, the thermal efficiency for present purposes may again be related to the expansion ratio V/v, which in this case is considerably higher than in the petrol engine case with resultant improvement in fuel consumption.

The flame temperature during combustion will also be in the region of 2,500°C. but, due to defective air utilisation, the heat of combustion is diluted to some extent and the maximum temperature spread over the total air in the combustion chamber will be reduced to about 1,800°C.

The Diesel engine has not been widely used in aviation but one engine which saw considerable service before the 1939-45 War was the Junkers Jumo engine, the results from which are also included in Table I.

It will be apparent that the cycle of operations described, particularly when referred to the two-stroke engine, is very much more adaptable for compounding purposes than the spark ignition case, for the following possible variables exist:

(*a*) In the absence of detonation or pre-ignition troubles the compression ratio and the degree of

supercharge may be varied to suit design requirements.

(*b*) The maximum cylinder pressures are to some extent controllable by variation in the rate of fuel input.

(*c*) Back pressures in the exhaust system need not be an embarrassment and are in fact essential when high degrees of supercharge are to be used.

(*d*) An excess quantity of air, over and above that required for combustion is passed through the engine, this serving as an internal cooling agent which also reduces the mean temperature of the exhaust gases.

It will be seen later that these possibilities may be turned to very good account in the compound engine and it may be stated here that the two-stroke Diesel cycle forms the ideal basis for compounding.

2.3. THE GAS TURBINE

Discussion here is limited to the propeller-turbine engine as it is this arrangement which is of interest relative to the compound case.

The basic cycle on which this engine operates is shown in Fig. 4(*c*). Combustion takes place at constant pressure and the basic thermal efficiency is again governed by the volumetric expansion ratio which, in the present state of compressor and turbine development, is limited to a lower value than that employed in either the Diesel or the spark ignition motor. If such an engine burned all the air passed through it the temperature of combustion would again be in the region of 2,500°C. and this is the continuously maintained temperature at which gases would enter the turbine. This temperature is prohibitive and with available materials and design technique, the temperature at the inlet to the turbine is limited to about 1,100°K. To achieve this reduction in temperature, air to the extent of about $3\frac{1}{2}$ times the amount actually required for combustion is therefore passed through the engine to provide temperature dilution.

When such an arrangement is associated with a piston engine to form a compound system such high excess air factors become unnecessary, for the reduction in gas temperatures is achieved by virtue of the work done in the piston engine cylinders and the compressor and turbine dimensions for a given rate of fuel consumed are thereby greatly reduced.

The objection may be raised that the figures here quoted for expansion ratio and turbine inlet temperature in the propeller-turbine engine are lower than some which are projected at the present time. Although this is appreciated it does not affect present considerations relative to the compound cycle and in any case it will be seen later that most of the developments which permit improved performances of the propeller-turbine are also of direct application to the compound engine.

2.4. THE COMPOUND ENGINE

In the compound engine the cycle of operations is shared between a two-stroke Diesel engine and a turbine, exhaust gases from the engine being fed into the turbine. The back pressure imposed by the turbine on the engine cylinders establishes the lower pressure level of the operating cycle in the cylinders and also determines the degree of supercharge necessary to pass the required quantity of air through the engine.

TABLE I

COMPARATIVE PERFORMANCE OF PISTON ENGINES

Type of engine	*Actual engine*	*Fuel*	*Max. S.H.P. at take off*	*Max. S.H.P. per litre*	*Max. S.H.P. per in.² of piston area*	*Specific weight lb. per S.H.P. at take off*	*Specific fuel consumption lb. per S.H.P. per hour. Sea level at 60% T.O. power*
PETROL ENGINES	Napier Sabre VA	100/130 Grade	2,550	69·5	5·43	0·976	0·50
	Napier Sabre VII	100/130 Grade + water	3,050	83·2	6·5	0·840	0·50
	* Wright Compound	115/145 Grade + water	3,700	67·3	6·97	0·92	0·400 †
TWO-STROKE DIESEL	Junkers Jumo 205E	Diesel fuel	600	36·0	3·73	1·910	0·345
COMPOUND * DIESEL	Napier Nomad	Diesel fuel	3,046	74·2	9·0	1·175	0·359
	Napier Nomad	Diesel fuel + water injection	3,480	84·8	10·25	1·027	0·345
	Napier Nomad	Diesel fuel + auxiliary combustion + water	3,970	96·5	11·70	0·959	0·340

* Figures based on total S.H.P.

† 51 per cent. power—auto-lean mixture.

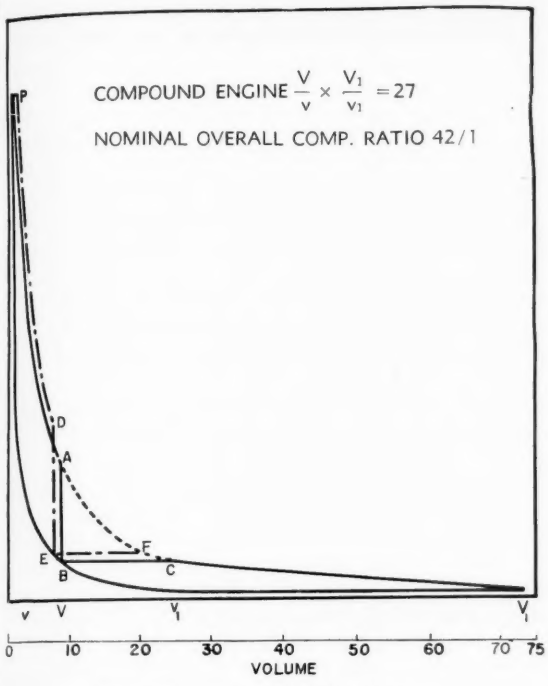

FIGURE 5. Typical Indicator Diagram.

The approximate form of the overall indicator diagram resulting from this combination is shown in Fig. 5, the division of work between the engine and the turbine being indicated by the line *ABC*, the difference in pressures between points *A* and *B* being that which exists between the pressure in the cylinder at the moment of exhaust release and the pressure at inlet to the turbine.

Considering first the characteristics of this complete diagram, it may be said that due to the high degree of compression which takes place outside the engine cylinders it is possible to use an overall compression ratio considerably higher than in the normal Diesel engine. Furthermore, the expansion line in the turbine extends down to atmospheric pressure and the result of these two factors combined is to produce a very high value for the overall expansion ratio. The actual expansion ratio which determines the limiting thermal efficiency however, is lower than this due to the losses which occur at transfer from the Diesel engine to the turbine and its value may be derived in the following way.

It will be seen that the overall diagram is compounded of two separate ones, first that for the Diesel engine which is similar in form to that of Fig. 4(*b*), and second that for the compressor-turbine combination which is similar to that of Fig. 4(*c*). The expansion ratio for the Diesel cycle is V/v, and that for the turbine V_1/v_1, so that the actual expansion ratio for the complete cycle is given by the product $(V/v)\times(V_1/v_1)$.

Within practical limits, for a given overall diagram the value of expansion ratio given by the product $(V/v)\times(V_1/v_1)$ and therefore the limiting thermal efficiency of the cycle, does not change materially with the position of line *ABC* indicating the division of work between the Diesel engine and the turbine.

But the division of work does exercise considerable influence on the dimensions and weight of the combined unit for a given maximum power and the selection of the various design constants affecting this point is one of the major problems in the early stages of compound engine design. Some indications of the nature of this problem may be obtained from a consideration of the following points.

Clearly the compound engine is subject to the same practical limitations as apply to other engines, so that the maximum cylinder pressure and the maximum turbine inlet temperature are reasonably well defined points determined by practice. If now the compound engine operated on an ideal air/fuel ratio and burned all its air, the temperature at point *P* would be about 2,500°C. and corresponding temperatures at various points down the expansion line would be defined. The maximum height for point *C* on the expansion line would therefore be fixed by the permissible turbine inlet temperature and this would also establish the supercharging pressure.

But it has been already pointed out that the Diesel engine does not consume all the air supplied to it and furthermore, that in the two-stroke cycle the excess air passed through the cylinders during the scavenging period can be controlled by porting design.

It is therefore possible to design the cycle so that the amount of excess air is a relatively high proportion of the total mass flow through the engine, in other words, to operate the engine on a higher overall air/fuel ratio. This excess air will mix with the exhaust gases and reduce their temperature so that to achieve the same limiting temperature at inlet to the turbine it now becomes possible to raise the position of point *C* on the expansion line to a new position *F*, the division of work now being indicated by line *D*, *E*, *F*. But this adjustment to the cycle has also raised the supercharging pressure, so that a greater quantity of air will be trapped in the engine cylinder thus permitting more fuel to be burned and a greater mean indicated pressure to be developed, as shown by the dotted expansion line.

The thermal loadings in the engine cylinders will set a limit to the extent of this adjustment but, as a practical point, it may be said that the passage of excess air through the cylinders not only gives ideal scavenging, it also provides a considerable degree of internal cooling, any resulting increase in its temperature being subsequently recovered in the turbine and therefore retained in the cycle. By exploiting this factor it is possible in the compound engine cylinder to achieve a rate of fuel burning which is much greater than in the normal Diesel engine, with a corresponding reduction in the dimensions and weight of engine required for a given power. This, coupled with the reduced size of compressor and turbine required for a given rate of fuel burning, which has already been referred to in Section 2.3, allows the size and specific weight of the compound power plant to be reduced to values which, when coupled with its

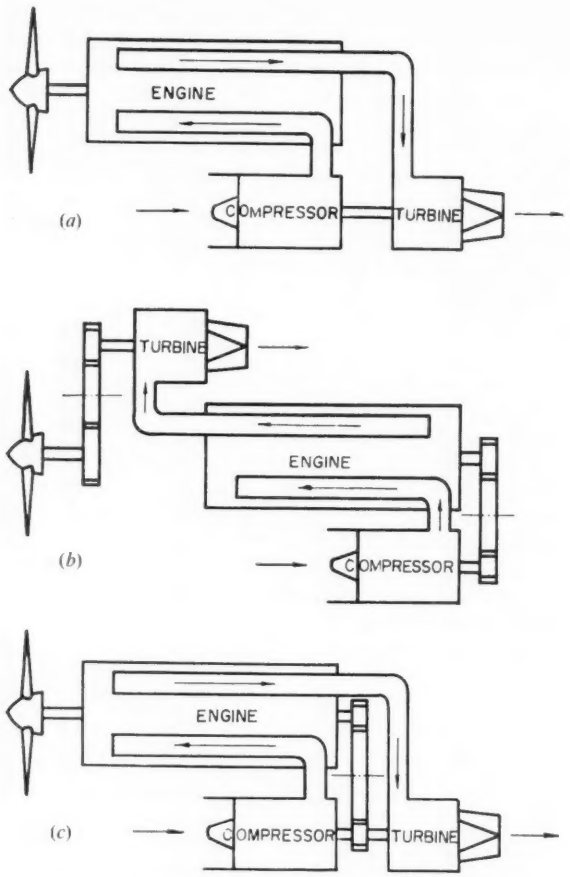

FIGURE 6. Mechanical arrangements for compounding

high thermal efficiency, render it more suitable than other power plants for certain applications.

The determination of the appropriate division of work in any particular case, therefore, involves consideration of a range of different overall air/fuel ratios, each involving corresponding adjustments to the size and pressure ratio of the compressor and turbine and the dimensions of the engine cylinders derived from the thermal and mechanical loadings imposed. The lightest possible power plant results when the best balance between these various factors is established in relation to the design targets.

Some characteristics of the compound engine as demonstrated by the Nomad are given in Table I to allow comparison with other types of engine.

3. Mechanical Arrangements for Compounding

For the purposes of this paper the compound engine is considered to consist of three major mechanical elements, first a two-stroke Diesel engine, second a gas turbine, and third a compressor. Investigators of compounding possibilities have sometimes proposed more complex arrangements involving a relative multiplicity of turbines, compressors and heat exchangers, designed with the object of extracting maximum possible energy from the fuel burned. In practice it seems unlikely that such complexity would be justified, for the thermal and aerodynamic losses involved in the gas transfer passages can exert serious influences on the actual results obtained. In any case, such arrangements are ruled out for aircraft purposes on the grounds of bulk and weight and discussion is therefore limited to possible combinations of the three basic elements concerned. Of these components the piston engine and the turbine contribute to the total power output, but the compressor absorbs power and must be driven.

From the purely mechanical standpoint three possibilities exist and their applicability is considered.

3.1. THE COMPRESSOR MAY BE DRIVEN BY THE TURBINE—ALL OUTPUT POWER BEING DELIVERED BY THE PISTON ENGINE (Fig. 6(*a*))

This arrangement constitutes in effect a two-stroke diesel engine equipped with a turbo-blower. It demands that over the whole operating range the turbine must be in power equilibrium with the compressor. Such a condition is impossible to achieve in practice, because while at full power the turbine can produce power in excess of compressor requirements, at low outputs it cannot satisfy the compressor demands due to the small exhaust energy available from the engine. This arrangement is therefore not applicable.

3.2. THE COMPRESSOR MAY BE DRIVEN BY THE PISTON ENGINE—ALL OUTPUT POWER BEING TAKEN FROM THE TURBINE (Fig. 6(*b*))

In this case the piston engine-compressor combination operates purely as a gas generator for the turbine. Here the piston engine and compressor must remain in power equilibrium at all operating conditions and the limitations arising from this requirement give rise to a number of disadvantages.

Firstly, at low power outputs the piston engine is prevented from making the contribution of which it is capable to the total power output, this resulting in very poor thermal efficiencies at part load conditions.

Secondly, due to the steep power law of the compressor against r.p.m., the piston engine at cruising conditions requires to operate at high piston speeds which results in greater wear and tear than necessary.

A further serious objection to this arrangement exists in relation to the power plant weight, for it will be seen that two sets of high ratio reduction gearing are required, one between the compressor and the engine crankshaft and the other between the turbine and the propeller shaft and both of these are called on to transmit high powers.

3.3. ALL THREE COMPONENTS MAY BE COUPLED TOGETHER TO FORM A COMMON MECHANICAL SYSTEM (Fig. 6(*c*))

In this system no requirement exists for power equilibrium between any two components and this allows the greatest possible flexibility in the choice of operating conditions for best performances over the

whole speed range. Furthermore, the lightest possible power plant results for the compressor and turbine, which have sympathetic characteristics on a speed basis, can be connected solidly together, the reduction gearing connecting them into the engine system being called upon to transmit only the difference in the power produced by the turbine and that demanded by the compressor.

This is the basic mechanical system employed in the Nomad engine.

3.4. ALTITUDE PERFORMANCE

The power plant layout suggested in Fig. 6(*c*) suffers from the defect common to all engines which depend upon a fixed ratio gear driven compressor in that its power falls off rapidly as altitude is increased, its power and fuel consumption curves for some part load condition being of the form shown by the broken lines in Fig. 7. Some improvement may be obtained by the provision of a two ratio gear between the engine and the turbo-compressor set, in which case these results would be modified in the manner shown. A much more satisfying solution to the problem can be obtained if an "infinitely variable gear" is employed, in which case the power and consumption lines can be maintained at sensibly constant values over a wide range of altitudes, as shown by the full lines *ABC* and *abc* in the diagram. In fact, the employment of such a gear confers still greater benefits, for it permits the gear ratio at any flight condition to be adjusted to take full advantage of air intake "ram" resulting from forward speed so that at all times the compressor power absorption is kept to a minimum, thus enabling enhanced performances to be obtained as shown by the lines *DEF* and *def*.

A further advantage of the variable gear is that it enables the compressor to be driven up to its maximum speed at any engine r.p.m., thus permitting greater maximum power altitudes to be achieved at low engine speeds.

Due to certain favourable factors which will be referred to later, it has been found possible to embody such an "infinitely variable gear" in the Nomad engine.

4. The Napier Nomad Engine

Having discussed briefly the basic problems involved in compounding, it is now possible to examine the practical solutions to these problems as demonstrated in the Napier Nomad and to consider the results obtained from this engine in relation to aircraft requirements.

4.1. MECHANICAL DETAILS

The mechanical layout of the Nomad is shown in Fig. 8 and it will be seen that this follows the arrangement suggested in Fig. 6(*c*), except that an "infinitely variable" gear has been interposed in the gear system between the turbo-compressor set and the engine; this permits a range of gear ratios to be selected for any crankshaft speed.

The diesel engine has 12 cylinders in banks of six, horizontally opposed on a six-throw crankshaft and the

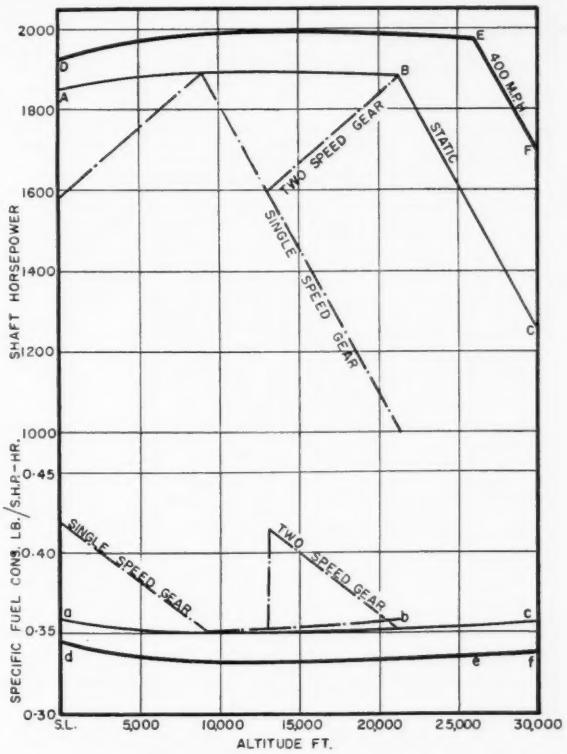

FIGURE 7. Altitude performance with fixed gear and variable gear superchargers.

cylinder design is of the simplest possible two-stroke type, using piston controlled ports with no valve gear of any kind. The scavenging system employed is that in which the incoming air is directed against the cylinder wall with an upward movement towards the combustion chamber, as shown in Fig. 9. This type of air flow not only gives effective scavenging of burned gases from the cylinder, but due to the well organised flow path it permits high air flows with minimum aerodynamic losses.

The combustion chamber is hemispherical in form with a centrally disposed injector having one central orifice and five equally spaced radial orifices, the only unusual feature being that the radial sprays are directed at the combustion chamber walls, experience having proved this to be beneficial.

The injector pumps which are in blocks of six, are of normal "jerk-pump" design, specially developed to deal with the high outputs and speeds of operation required.

The pistons, which are illustrated in Fig. 10, have Y alloy bodies but are fitted with austenitic steel tops designed to run at temperatures in the centre of the crown between 600° and 700°C. at full power. Oil cooling is provided behind the piston rings to ensure minimum temperatures at this point.

The uni-directional loadings on the connecting rods resulting from two-stroke operation permit the use of an unusual design, as shown in Fig. 11, both small and big end bearings being of the half bearing or "slipper" type.

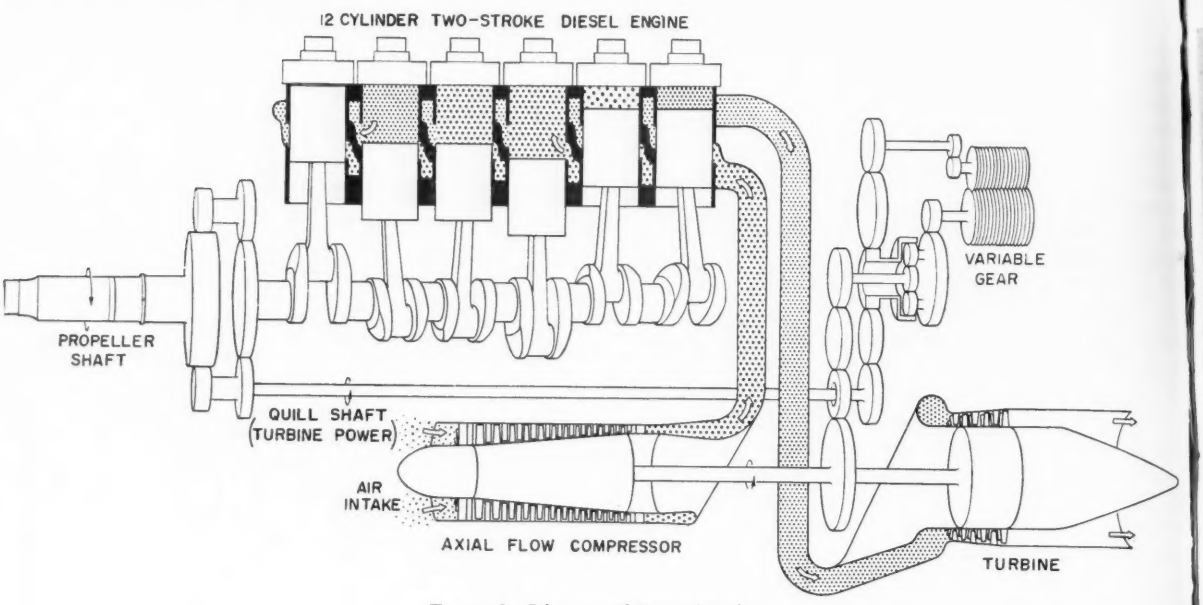

FIGURE 8. Diagram of Nomad engine.

with light straps as safety devices in the reverse loading direction.

The axial compressor has 12 stages and operates at a maximum pressure ratio of 8·25 : 1 with an air mass flow of 13 lb. per second and to extend the operating range at the low speed end, adjustable inlet guide vanes are fitted.

The three-stage turbine is mounted co-axially with the compressor and its blading is designed to extract maximum energy from the gases, the residual jet thrusts being small.

Both compressors and turbine are connected into the rear gear casing by shafts having toothed couplings at each end to allow for expansion effects.

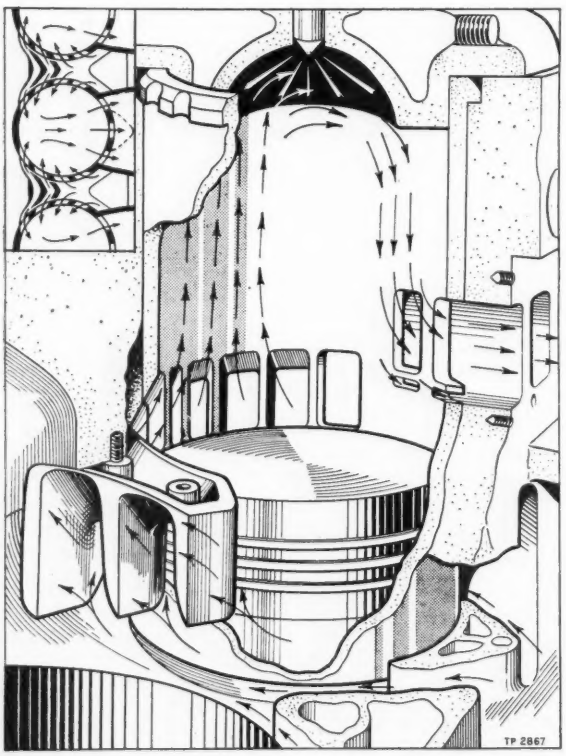

FIGURE 9. Arrangement of engine cylinder.

4.2. THE INFINITELY VARIABLE GEAR

This gear has been designed and developed by Napiers to suit the particular requirements of the Nomad application, but the basic scheme was evolved by Dr. Joseph Beier and developed in Germany before the 1939-45 War. It is an ingenious practical adaptation of the well known scheme in which two conical members are end-loaded together, the gear ratio being varied by sliding one cone over the other. The actual details of the Beier version of this basic scheme are as shown in Fig. 12. Here a "pack" of discs with narrow conical rims are mounted on a central shaft and spring-loaded to trap between them a series of coned discs carried on a planetary shaft, which is arranged to swing about a fulcrum to obtain changes in gear ratio. By attaching a gear to the planetary shaft meshing with one at the fulcrum, it is possible to arrange a constant mesh gear system so that changes in gear ratio can be made while running. It will be clear that a number of planetary shafts can be similarly disposed around the centre shaft and in the Nomad three sets of planetary discs are used.

This type of gear would normally be classified as a "friction" device but, in this particular application, the drag force between the discs is obtained by fluid shear of the oil film at the contact points, the end loads being

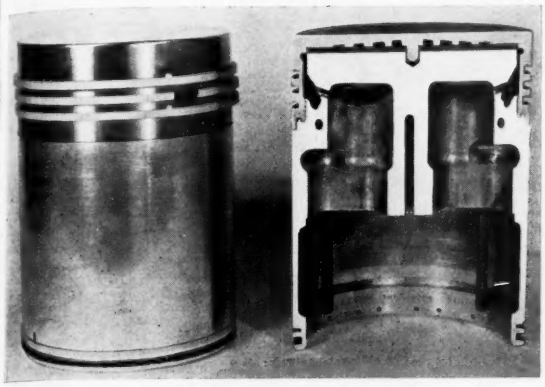

FIGURE 10. Arrangement of piston.

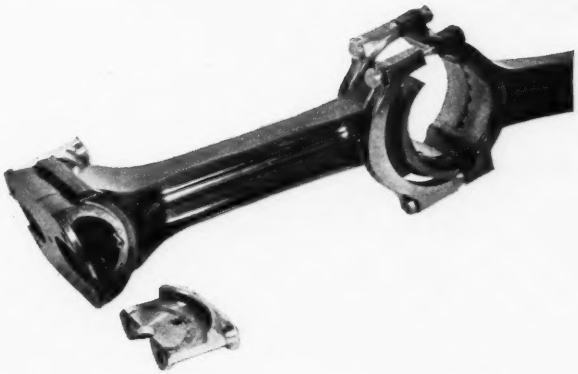

FIGURE 11. Arrangement of connecting rod.

adjusted in relation to the lubrication conditions to obtain the most efficient operation.

A great advantage of this device is that it transmits power through a multiplicity of contact points, the number of which can be varied experimentally to achieve most satisfactory performances.

To reduce the dimensions and weight of the variable gear to a minimum, it is connected into the gear system of the Nomad, as indicated in Fig. 13.

Here the speed reducing gear for the turbo-compressor set is of epicyclic form, the variable speed device being connected across two members of the epicyclic train. This, in effect, produces two mechanical systems in parallel, only about 30 per cent. of the total power flow being transmitted through that part of the system in which the speed varying device is fitted.

The arrangement of this complete system in the Nomad is shown in Fig. 14.

4.3. THE COMPLETE ENGINE

A longitudinal section through the engine is shown in Fig. 15, the layout following closely the diagrammatic arrangement of Fig. 8.

Figure 16 shows the engine in cross section and indicates clearly the vertically divided magnesium crankcase and the aluminium cylinder blocks, the whole structure being bolted together by steel through-bolts. It will be seen that "dry" liners are employed, the liners themselves being of chromium-copper material chromium plated in the bores. The dimensions on this drawing show that the frontal area of the engine is small, in piston engine terms, the shape being convenient for cowling purposes.

Figure 17 is a photograph from one side and shows that the engine is suspended from four pick-up points, two at the front end of the crankcase and two on the rear gear casing. This arrangement is convenient from the installation point of view and gives maximum accessibility, particularly to the compressor and turbine.

Starting is by electric motor and as the compression ratio in the engine cylinders is insufficient to give self-ignition under these conditions, spark plugs are fitted in each cylinder head activated from a high energy system.

A three-quarter front view is shown in Fig. 18.

4.4. ENGINE OPERATION AND CONTROL

The engine is equipped with a single lever control system which relates the variable factors together to produce a pre-determined power law against r.p.m. The speed function is controlled by a normal mechanically set constant speed unit varying propeller pitch, each

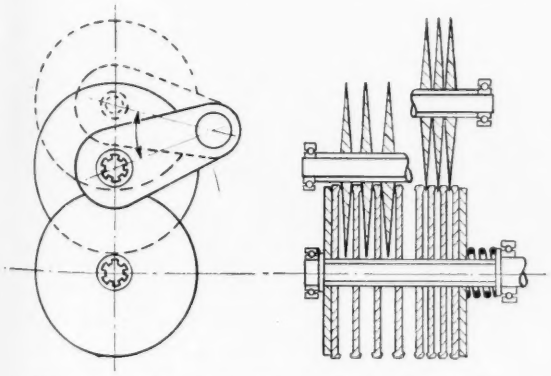

FIGURE 12. Diagram showing operation of variable gear.

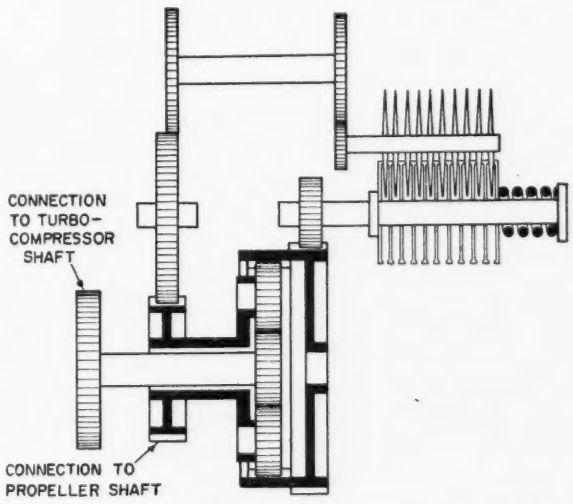

FIGURE 13. Connection of variable gear to epicyclic train.

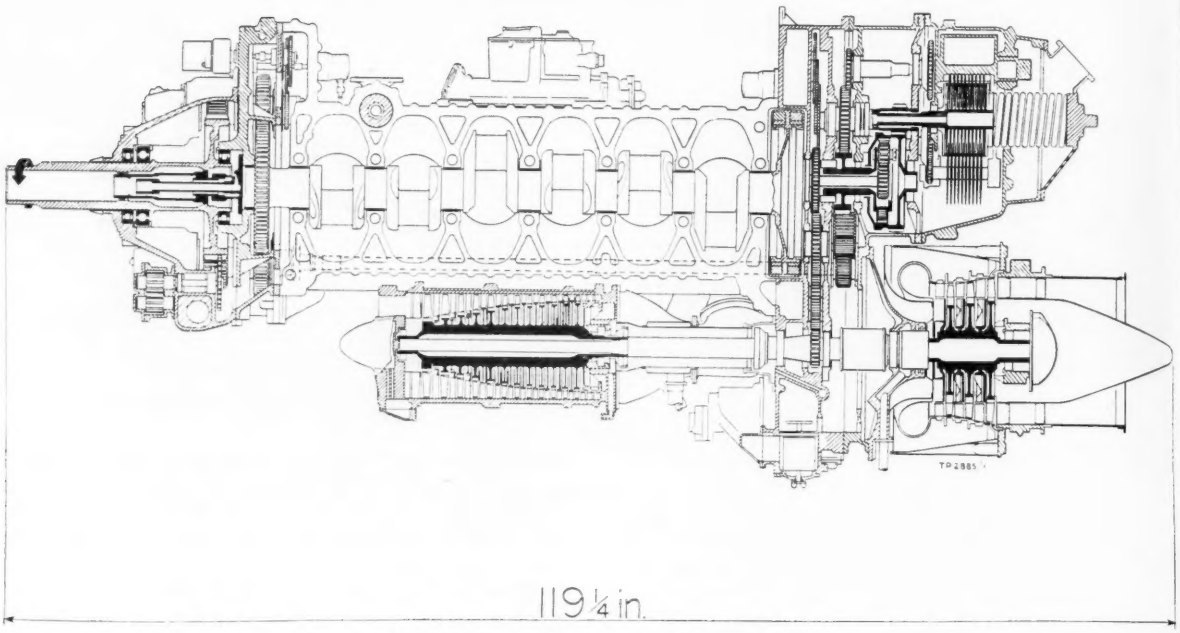

FIGURE 15. Longitudinal section of Nomad engine.

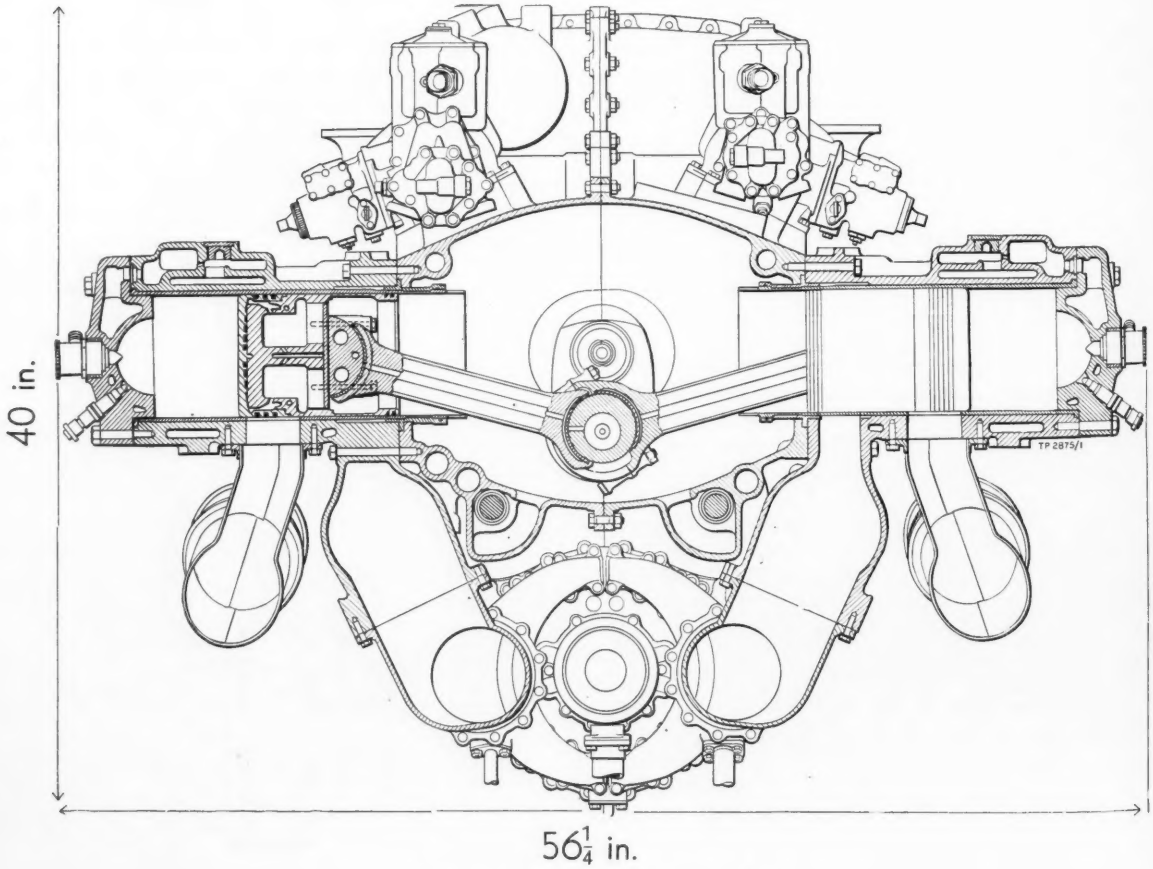

FIGURE 16. Cross section of Nomad engine.

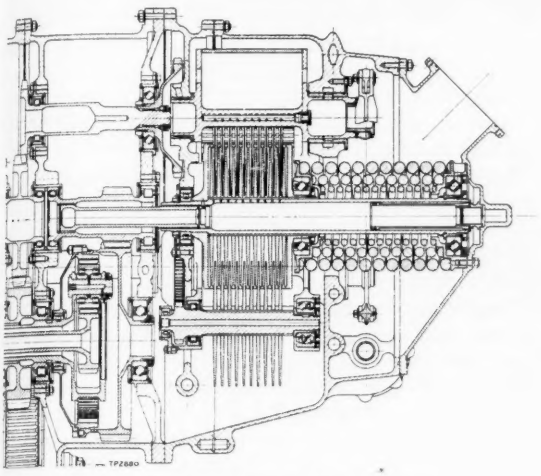

FIGURE 14. Variable gear as fitted to engine.

speed selection being mechanically related to a rack setting on the fuel pumps governing the fuel flow, and to a selected boost pressure. The boost pressure setting is applied to a normal type of variable datum boost control unit, the servo piston of which operates the setting of the infinitely variable gear, the ratio of which is thereby automatically adjusted to maintain the selected boost pressure. Any selected r.p.m., fuel flow and boost pressure are in this way automatically maintained with increasing altitude until the maximum permitted r.p.m. of the turbo-compressor set is reached, this corresponding to the maximum power altitude for that particular engine condition. Above this point re-setting mechanism is provided which reduces fuel flow in sympathy with decreasing boost. The engine is therefore capable of maintaining a constant selected boost and power with corresponding fuel consumptions, over a wide range of altitudes which at 60 per cent. of take-off power extends from sea level up to 25,000 ft.

For optimum matching over the full power and altitude range of the engine a variable capacity compressor is necessary. This change in capacity is achieved by an automatic device which adjusts the incident angle of the compressor inlet guide vanes to a function of inlet pressure with a variable datum controlled by boost pressure.

5. Nomad Engine Performances

Brief reference was made in Section 2.4 to some factors influencing the division of work between the diesel engine and the turbine. In the actual case this problem is more complex than was indicated, for there are other aspects of engine performance, such as altitude requirements and the fuel consumptions at part loads, which must also be considered. Taking all the design requirements into account and also taking advantage of considerable experimental data, the major operating factors used in the Nomad and the resulting performances, are summarised below.

5.1. TAKE-OFF PERFORMANCE OF BASIC ENGINE

The supercharging by pressure used in the diesel engine for take-off is 89 lb./in.^{2} (abs.), this corresponding to a volumetric compression ratio of 3·36:1. When this is multiplied by the actual compression ratio in the engine cylinders based on effective stroke (8:1) we arrive at an overall compression ratio of 27:1.

Allowing for air intake and ducting losses the pressure ratio demanded from the compressor to provide the supercharging pressure of 89 lb./in.^{2} (abs.) at sea level is 6·28:1. The maximum pressure ratio of the compressor at its top speed is 8·25:1 and this permits the take-off boost to be maintained up to 7,750 ft. by variation in gear ratio.

The air/fuel ratio dictated by the cylinder performance requirements is 40 : 1, corresponding to an air mass flow of 13 lb. per second, and when operating with a maximum pressure limitation of 2,200 lb./in.^{2} a brake mean effective pressure of 205 lb./in.^{2} is developed in the cylinders which have a bore of 6 in. and a total stroke of 7·375 in., giving a swept volume of 41·1 litres.

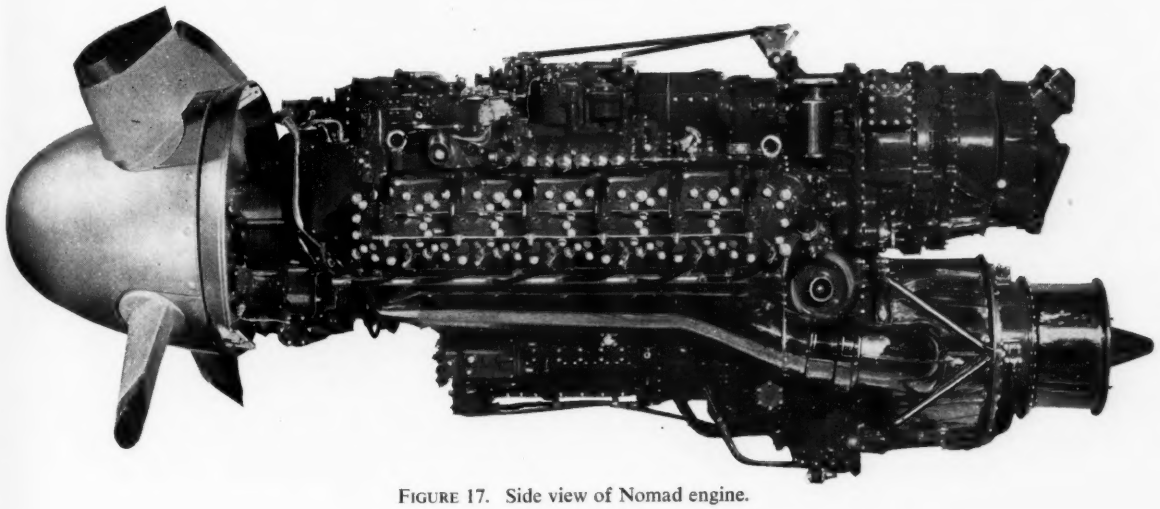

FIGURE 17. Side view of Nomad engine.

At the maximum crankshaft speed of 2,050 r.p.m. the piston speed is 2,520 ft. per minute and the b.h.p. developed by the diesel engine alone, neglecting any contribution from the turbine, is 2,660, or 64·7 b.h.p. per litre.

The ability of the engine to operate at such high outputs is an indication of the benefits derived from the excess air factor, for the recorded piston ring temperatures at this power are no higher than those on a normal diesel engine developing less than half the power at equivalent piston speeds.

The pressure drop across the engine cylinders at take-off power is 13·0 lb./in.², giving a turbine inlet pressure of 76 lb./in.² (abs.) and the temperature at the turbine inlet is 934°K. The pressure ratio across the turbine at sea level is 4·6:1 and this corresponds to a volumetric expansion ratio of 3·35:1, which, when multiplied by the diesel expansion ratio of 8:1, gives an overall expansion ratio of 27:1.

The power developed by the turbine at sea level is 2,250 h.p. of which 1,840 h.p. is absorbed in driving the compressor, so that there is an excess of 410 h.p., less a slight power loss of about 20 h.p. in the variable gear, as an addition to the diesel engine output. The equivalent horsepower developed by the engine, taking into account the small amount of jet thrust available, becomes 3,135 h.p. or 76 h.p. per litre.

The net dry weight of the engine is 3,580 lb. so that the specific weight is 1·175 lb. per h.p.

The specific fuel consumption based on the equivalent power is 0·345 lb. per E.H.P. per hour.

5.2. TAKE-OFF PERFORMANCE WITH WATER INJECTION

With the high degree of supercharge used for take-off the charge air temperature is high, about 247°C. at sea level. This could be reduced by after-cooling but this would involve additional bulk and weight, together with a serious loss of energy from the cycle. The charge temperature can be reduced most conveniently and its density increased without energy loss, by the injection of water into the inlet manifolds and when this is done a greater quantity of air can be packed into the engine cylinders and the power output still further increased. Using water injection in this way the equivalent power of the engine is increased to 3,580 h.p. (87·2 h.p. per litre) and the specific weight is reduced to 1·0 lb. per h.p. The specific fuel consumption is also reduced to 0·336 lb. per E.H.P. per hour.

5.3. TAKE-OFF PERFORMANCE WITH AUXILIARY COMBUSTION

A further possibiity for increasing the maximum power output arises from the presence of excess air in the exhaust manifold between the engine and the turbine for, at the expense of a slight increase in the turbine inlet temperature, a small quantity of additional fuel can be injected and burned at this point. This extra fuel is burned at low expansion ratio and therefore at low efficiency, but the effect on the overall specific consumption is small.

This system of auxiliary combustion can be used in association with water injection and for a turbine inlet

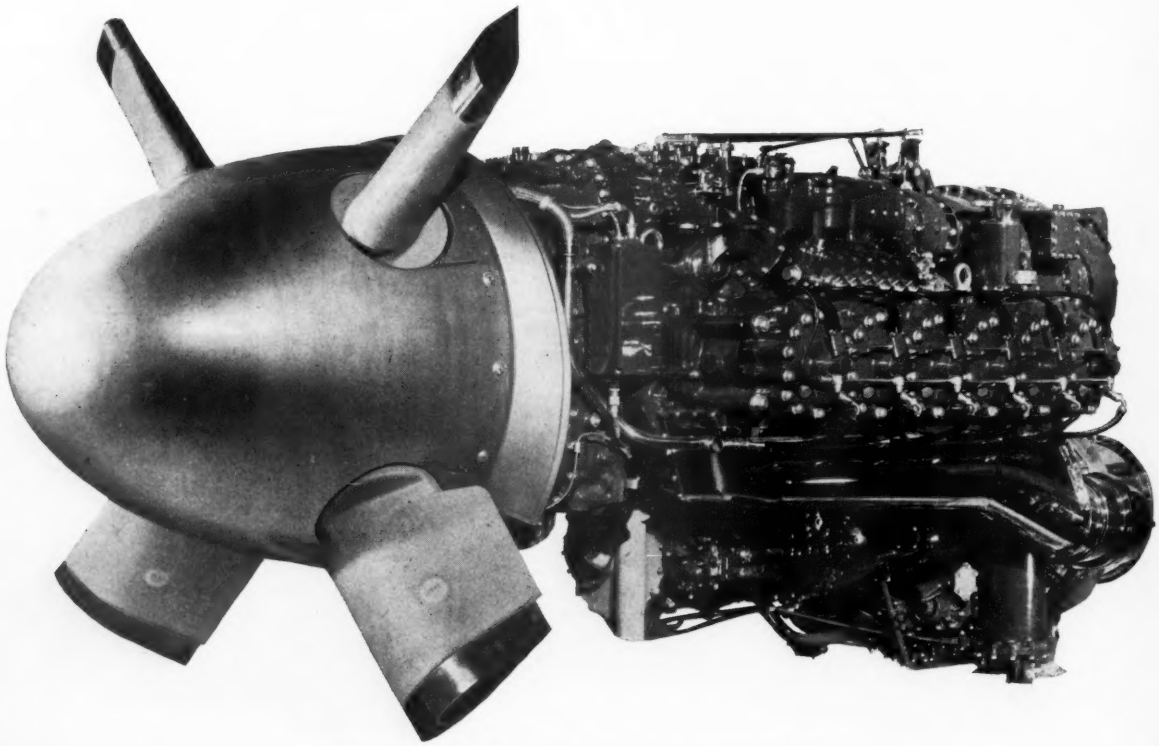

FIGURE 18. Three-quarter front view of Nomad engine.

temperature of 1,020°K. the take-off power can be increased to 4,100 h.p. (99·6 h.p. per litre), the specific weight being thereby reduced to 0·93 lb. per E.H.P. The specific fuel consumption in this case is increased to 0·374 lb. per E.H.P. per hour.

The take-off performances against altitude for the three conditions referred to are illustrated in Fig. 19.

5.4. CRUISING PERFORMANCES AT ALTITUDE

The power law to which the engine is controlled over the speed range under sea level static conditions is shown in Fig. 20, the shape of this curve being devised to maintain optimum thermal efficiency and altitude performance over as wide a range as possible and also, to suit control requirements of the propeller.

On the same diagram are shown also the corresponding diesel, turbine and compressor powers and it will be observed that at 1,500 r.p.m. the turbine power exactly balances that absorbed by the compressor. At lower engine speeds the power developed by the turbine is below that demanded by the compressor and this power defficiency has to be fed in from the diesel engine.

The engine r.p.m. at which balance occurs between the turbine and compressor powers, varies with altitude and forward speed but over the useful cruising range the power transmitted through the infinitely variable gear is relatively small.

From Section 4.4 it will be clear that as altitude is increased with the engine operating at any point on the inter-connection curve, the boost pressure appropriate to that condition will be maintained by progressive adjustment of gear ratio until the limiting r.p.m. of the turbo-compressor set is reached, this representing the maximum power altitude for that particular operating condition. Bearing in mind the reduction in compressor work necessary to achieve the selected boost pressure due to forward speed, and the improvements in compressor and turbine efficiency derived from increasing altitude, there results a continuous increase in power output until the maximum power altitude is reached, with corresponding reductions in specific fuel consumption.

The power inter-connection curve extended up to the maximum power altitudes at each value of r.p.m., with a forward speed of 300 knots, and the corresponding component powers, are shown in Fig. 21. It will be observed that over the whole operating range at these conditions the specific fuel consumption remains sensibly constant between 0·34 and 0·36 lb. per S.H.P. per hour.

Figure 22 shows performances at varying altitudes with selected engine ratings and again the constant values for both power and fuel consumptions are worthy of note. The best fuel economy is achieved at the recommended cruising rating between 15,000 and 25,000 ft., where for a power of 2,000 E.H.P. the specific fuel consumption is 0·326 lb. per E.H.P. per hour.

5.5. GENERAL CHARACTERISTICS

Apart from the performance figures which have been quoted, there are two further characteristics which arise from the nature of the operating cycle and which assume some importance.

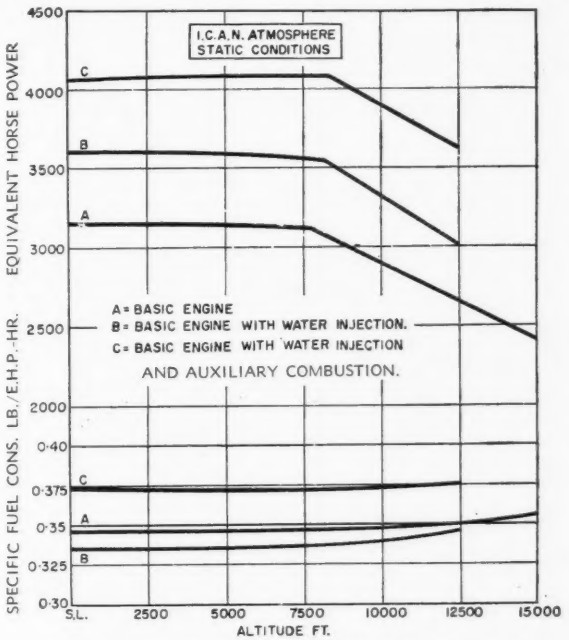

FIGURE 19. Take-off powers against altitude with fuel consumption.

Firstly, there is extreme adaptability in the matter of fuels. Designed to run on diesel fuel for maximum economy, the engine will operate equally well on kerosine or wide-cut gasoline.

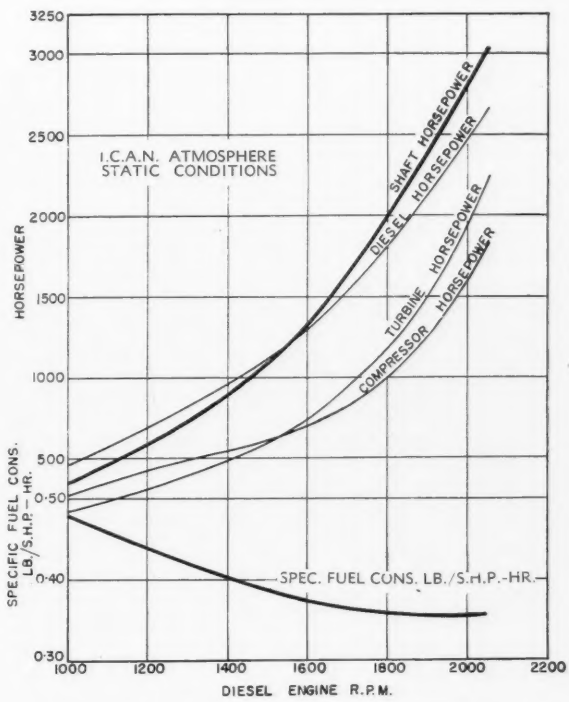

FIGURE 20. Sea level static inter-connection power curve.

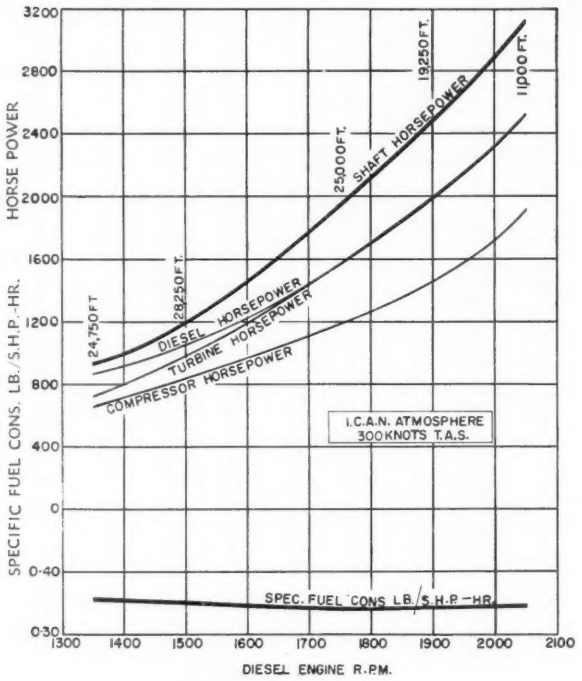

FIGURE 21. Altitude inter-connection power curve.

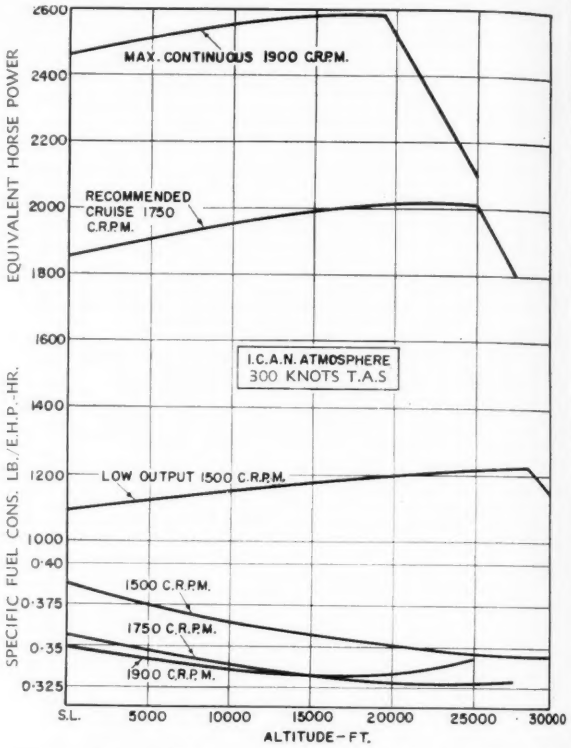

FIGURE 22. Altitude cruising curves with fuel consumptions.

Secondly, the engine is insensitive to increases in ambient temperature, losing less than 2 per cent. of its take-off power for each 10°C. increase in temperature.

6. The Nomad Engine in Modern Aviation

Consideration of the performance figures which have been quoted demonstrates that the outstanding characteristics of the Nomad engine are its low fuel consumptions, which are maintained unimpaired over a wide range of powers, altitudes and flight speeds, and its ability to use cheap fuels.

These two factors combine to provide great economy in operation, but apart from this the smaller quantity of fuel consumed, as compared with other engines, for a flight of given duration reduces the proportion of all-up weight of the aircraft absorbed by fuel storage, thus enabling the useful payload to be increased. Alternatively, the original payload may be flown over a greater distance.

There are specific aircraft applications in which these characteristics can display very definite operational advantages over other types of power plant and it is necessary to consider these in two categories, those applied to military purposes and those for civil use.

In the military field economy of operation is a secondary consideration; it is the ability to perform a defined operation more effectively which assumes greater importance. On this basis the Nomad engine constitutes the most suitable power plant for Maritime Reconnaissance aircraft, which have to undertake prolonged periods of search at low altitudes and low flight speeds at considerable distances from base. Here the long range propensities of the engine, coupled with the ability to employ any desired type of flight plan without significant change in the quantity of fuel consumed, enable maximum effectiveness of the military operation to be achieved with minimum total duration of flight.

A further military application in which the Nomad shows to advantage is in the tactical role of Army support. In such cases the necessity for large apertures in the fuselage for troop and supply dropping makes pressurisation difficult, if not impossible, and the ability to carry maximum payloads at altitudes below that at which pressurisation becomes necessary is one which is derived directly from the operating characteristics of the engine.

It is in the civil field however, and particularly in air freighting operations, that the Nomad can make its biggest contribution to aviation at the present time and it was, in fact, for this purpose that the engine design was originally undertaken.

There can be little doubt that the greatest opportunity for expansion in the aviation industry in the immediate future lies in the development of air freighting services; there are tremendous potential markets in this field which are almost entirely unexplored, even in the U.S.A. where more progress has been made than elsewhere.

For freighting purposes economy is the vital factor and it seems certain that satisfactory operating economy will be achieved only by aircraft designed primarily for freighting. The development of such aircraft is of vital

economic importance to this country at the present time, not only in relation to the business which can result from expansion in freighting activities, but also in potential sales of the aircraft concerned. There exist already two such British aircraft which are of noteworthy performance in this particular field, the Bristol Britannia for the longer ranges and the Blackburn Universal Freighter for the shorter routes.

With the co-operation of the aircraft companies concerned, design studies have been made by Napiers to assess the effects on operating characteristics of these aircraft if the engines now fitted were replaced by Nomads. In addition, to cater for cases in which the volume of traffic would not justify the use of such large aircraft, a similar study was undertaken relative to a civil version of the Fairchild Packet.

The results of these studies are shown in Figs. 23 and 24. It is not possible here to describe in detail the methods by which these curves have been derived; it must suffice to state that they are based on the standard S.B.A.C. method of computation, but the fuel costs which have been used are given below; being average World prices excluding U.S.A.

Aircraft	*Engines*	*Fuel*	*Fuel cost per gallon*
Bristol Britannia	Proteus	Aviation turbine fuel	1/10d.
Blackburn Universal	Centaurus	Petrol 100/130 grade	2/7¼d.
Fairchild Packet	Wright Compound	Petrol 115/145 grade	2/9d.
All three aircraft	Nomad	Diesel fuel	1/8d.

For comparative purposes the characteristics of three other well known aircraft, the Bristol 170 Freighter, the Lockheed Super-Constellation and the Douglas DC-6A with their existing engines are also shown on the curves.

Figure 23 shows the change in payload resulting from the fitting of Nomad engines and Fig. 24 shows the improvement in direct operating costs per ton-mile.

Examination of these results indicates in no uncertain manner the contribution which the Nomad engine can make to the problem of economical freighting over short or long ranges of flight.

ACKNOWLEDGMENTS

The author wishes to express his thanks to the Board of Directors of D. Napier & Son Ltd. for permission to publish this paper, and to the Bristol Aeroplane Co. Ltd. and Blackburn and General Aircraft Ltd. for their agreement to display the results shown in Figs. 23 and 24. He is also grateful to his colleagues at Napiers who gave assistance in the preparation of the paper.

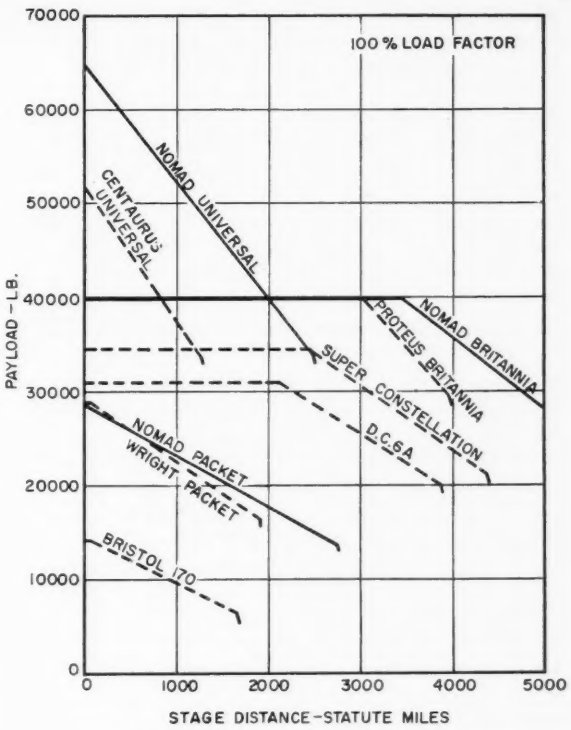

FIGURE 23. Variation in payload with stage distance.

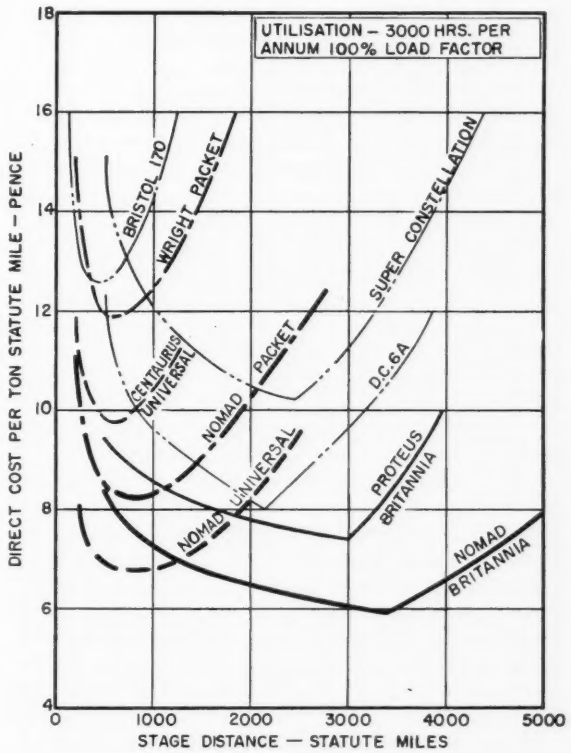

FIGURE 24.

Discussion

AIR COMMODORE F. R. BANKS (Associated Ethyl Co. Ltd., *Fellow*): Both Mr. Chatterton and he, and Dr. Moult, who was also present, had their early experience in an excellent engineering firm—Peter Hooker Ltd., of Walthamstow; that was why they were such good engineers!

It was not generally known that Hooker's took the licence for the Gnome engine in, he believed, 1913. And then, after the First World War, they threw out the obturator ring, which was supposed to be essential to the Gnome's good operation. With Hedley Thomson, and the late lamented Colonel Devereux, "Y" alloy pistons were made for the Gnome engine, having quite ordinary rings; and they worked better than the old obturator.

Compounding was not new, and he thought some acknowledgment should have been given Sir Harry Ricardo for, he believed, the original conception of this particular system of compounding a two-stroke engine. To Messrs. Napier certainly went the credit for the design and the intriguing mechanical development attending such a complex system. Having looked at the Nomad many times, he could confirm that there was some very clever engineering in it—not the least of which had been to get practical operation of a variable speed gear box. While the motor-car people never spent money on development to the extent that was done in aviation (because they could not afford to do so), he felt that this variable speed gear might have good application in the motor vehicle.

The question of low specific fuel consumption was obviously of the greatest importance, but there were other things which must also go with it in the aviation engine—such as low installed weight and aerodynamic "drag." Mr. Chatterton had made a very good case for the Nomad, in the particular aircraft for which it was most suitable. Some thought that the lowest specific fuel consumption inferred the maximum air miles per gallon, but that was not necessarily so. Only the other day he saw an analysis of the performance of two turbo-jet engines in a certain aircraft, where the engine giving the higher specific consumption produced as good a range as the more economical unit—because the former used fuel at a somewhat greater rate and the aircraft lost weight more rapidly during its trip and, therefore, needed less power at the cruising condition.

What was also interesting in history was that, in 1927, Messrs. Napier produced an engine, a racing engine, having the lowest ever specific consumption and, probably the highest thermal efficiency recorded for an internal combustion piston engine—the Schneider Trophy model Napier Lion. It might seem curious that such an engine should give a very low specific consumption; but it could be explained by the fact that it was an unsupercharged engine with very high mechanical efficiency—having roller bearings and a 10/1 compression ratio. Its consumption was about 0·32 lb./b.h.p./hour. He believed Sir Harry Ricardo was responsible for the confirmatory tests on the Lion, after the 1927 Contest.

He had one question for Mr. Chatterton. Was the effective compression ratio of a two-stroke calculated at the point where the piston "breaks" the exhaust ports?

J. F. ALCOCK (Ricardo & Co. Ltd.): He was impressed by the courage of Mr. Chatterton and Napiers in going to the high peak pressure of 2,200 in.^{2} and by the design skill needed to keep the specific weight so low in spite of these high pressures.

Air Commodore Banks had mentioned Ricardo's early work on gas-generator engines and some details might be of interest.

They started work on compounds in 1929 and traversed a kind of "Rake's Progress" through most of the schemes which Mr. Chatterton rightly rejected, mainly because those were the only methods then practicable. They started with a petrol engine, since in 1929 the high-speed Diesel was insufficiently developed. This proved impracticable, because of detonation and very high exhaust temperature. Later they tried four-stroke Diesels; those taught them that suitably-designed engines could stand up to the high pressures and heat flow of compound operation, but four-strokes were too heavy.

In 1939 they were asked by the Air Ministry to put up a proposal for a gas-generator installation with an independent 3,000 h.p. turbine fed from a number of engine-compressor units as in Mr. Chatterton's Fig. 6(*b*).

DIAGRAMMATIC LAYOUT OF GAS GENERATOR PLANT.

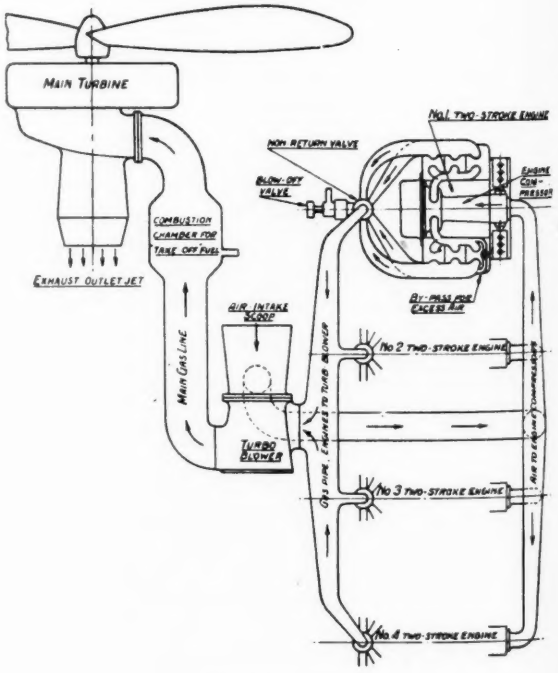

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FIGURE A.

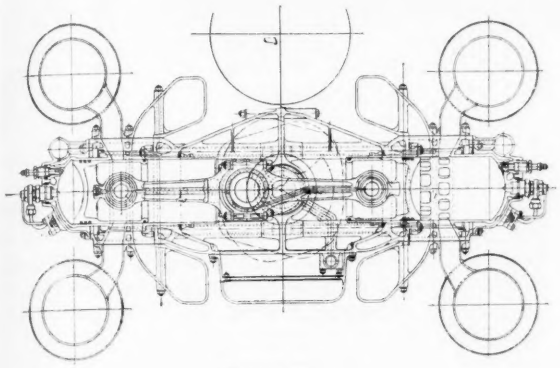

FIGURE B.

This arrangement had the drawbacks mentioned by the author, but was in their case necessitated by the aircraft requirements.

Figure A showed the set-up, as submitted in 1940. Each turbine was fed from four gas-generator units with rather elaborate valving needed to put individual engines on and off the line and to prevent back-flow through a stopped unit. There was a separate turbo-blower to maintain power at altitude and after-burning for take-off.

The engine design was shown in Fig. B. The cross-section bore some resemblance to the author's Fig. 6, but the scavenging was different, there being complete rings of exhaust and scavenge ports, one above the other; this arrangement, although less efficient than the Nomad loop scavenge, was used to avoid asymmetrical heating of the piston. The big-ends, and little-ends too, were of quite orthodox design. It was interesting to compare the estimated performance of this plant with the actual Nomad figures:—

	Ricardo, 1940 *Est.*	*Nomad Actual*
	Peak pressure 1,200 p.s.i.	Peak pressure 2,200 p.s.i.
H.P./in.^{2} piston	7·9	9·0
Dry wt./h.p., lb.	1·3	1·175
Cruising Consumption, lb./E.H.P.hr. (18,000 ft. 250 kts.)	0·365	0·33

For each of these figures the Ricardo estimate was about 10 per cent. higher than the Nomad figures, although it would be safer to ascribe this coincidence to a lucky cancellation of errors than to a gift of prophecy!

Three single-cylinder units were made and run, two of the Fig. B type, and the third with sleeve-valve-controlled exhaust ports. These were tested with independently-compressed scavenge air and a throttle to simulate the turbine; they ran between them some 3,800 hours. Output ranged up to a B.M.P. of 300 p.s.i. at a piston speed of 1,750 ft./min. with peak pressures up to 1,800 p.s.i.

Throughout the work they were surprisingly free from the thermal troubles one might expect with those high outputs. Mechanical trouble, too, was rare, although there was some ring and bore scuffing at peak pressures above 1,500 p.s.i.

A problem with two-stroke compound units having one or few cylinders was the measurement of exhaust temperature needed for estimates of turbine output. Exhaust thermometers were useless, since they did not average correctly the alternate puffs of hot and cold gas they received. Ultimately they used an exhaust calorimeter and calculated the temperature from the exhaust heat, mass and composition.

He would like to ask some questions:—

(1) Did the high cylinder pressures cause abnormal ring or bore wear?
(2) When idling, must the spark be kept on?
(3) There appeared from Fig. 10 to be oil-cooling grooves on the underside of the crown, which was stated to be at 600-700°C in the centre. Did that not cause carbonisation?
(4) The power transmitted through the Beier gear appeared to be very high for a friction gear and one would like to know the maximum figure. For such powers there must be very high contact pressures, and he imagined that there was boundary lubrication rather than a hydrodynamic film.

DR. E. S. MOULT (de Havilland Engine Co. Ltd., *Fellow*): Although Peter Hooker Ltd., took a licence to manufacture Gnome engines in 1913 (and thank goodness, for the sake of the fighters of the First World War, they did so), neither he nor Air Commodore Banks nor Mr. Chatterton were there at that time!

He was glad that public tribute had been paid to the Napier work in the field of turbo-supercharging as early as 1924. From the National point of view it was a pity, in retrospect, that this development was not continued; it might have speeded the coming of the gas turbine and it would certainly have improved the performance of bomber aircraft.

Historically, so far as aviation was concerned, they must give pride of place to Rateau's work in France; in America The General Electric Co. had pioneered the turbo-supercharger and had brought it into successful production for the Boeing Flying Fortresses of the Second World War. For fighter aircraft, he felt they had done the right thing in Great Britain in developing the multi-speed supercharger which, in conjunction with ejector exhaust pipes, had given the necessary performance in a simpler and lighter manner.

The Nomad was a water-cooled engine and it would be helpful if Mr. Chatterton could indicate the magnitude of the heat losses in terms of, say, a percentage of the crankshaft power. While the charge-density and turbulence were high, there was, he realised, a good deal of internal cooling from the scavenge air. It was important to have some ideas about radiator size in assessing the installed weight rather than the net dry weight.

Had there been any special vibration problems in coupling a diesel engine with its cyclic speed fluctuations to the high inertia of a turbine-compressor unit running

at constant r.p.m.? In other words, was there transmission of torsional vibration which was not overcome by the quill shaft shown in Fig. 8?

Could any data be given on the rate of acceleration of the engine when opening up from idling speed? He asked this because in another connection they had experimented with a turbo-supercharger applied directly to an unsupercharged petrol engine. Acceleration to zero (atmospheric) boost was good but beyond this the engine waited for the turbine to gather speed while the turbine waited for the exhaust from the engine! On a propeller load, the process was decidedly sluggish.

In making comparisons it was essential to consider all aspects and, as Air Commodore Banks had pointed out, they must not be overwhelmed by specific fuel consumption, important as it was. In this connection the turbo-charged petrol engine was a keen competitor and, as typified by the Wright Turbo-Compound they saw it in many of the latest American prototypes. In round figures the difference in cruising fuel consumption between the petrol compound and its Diesel counterpart would be about 0·05 lb./b.h.p./hour. At a cruising power of 2,000 h.p., this represented a fuel saving of 100 lb. per hour or a flight of five hours to recover an installation difference of, say, 500 lb.

Thus, in Figs. 23 and 24, the Nomad showed considerable advantage over the Centaurus when fitted to the Universal Freighter but these differences would have been narrowed had the Centaurus been fitted with an exhaust turbine. Where the comparison was on similar terms, as between the Wright Packet and the Nomad Packet (Fig. 23) there was little change in payload but a marked difference in the economics of operation (Fig. 24). Presumably, this economy arose mainly from the difference in costs of high-octane petrol and Diesel oil?

MAJOR J. R. GOULD: In Wilkinson's book on "Aircraft Diesels" which gave details of the aircraft Diesel engines built up to the middle of the last war, their development in the German Luft Hansa was described in detail. By using Diesel engines they entirely overcame the fire risk, which seemed to be the major point, and the fuel consumption was much lower than with petrol engines. The Luft Hansa was practically entirely equipped with Diesel engines, and it was stated in this book that efficiency was 50 per cent. better with Diesel engines than with petrol engines.

Had that been worked out for the Nomad engine? It seemed to him that it would entirely replace the petrol engine, because from the traffic operating point of view it was very important today to achieve greater efficiency, instead of using the enormous powers that were put into aircraft—3,000-5,000 h.p. in a flying boat, for instance, and on only one pair of wings. It seemed to him that aircraft today were getting too much engine and not enough wing lifting power. The Diesel engine offered a great saving in the weight of fuel carried, compared with the jet engine; for example, 37 gallons a minute seemed preposterous, being five times the amount of fuel consumed by a Diesel engine.

He would also like to know the number of hours between servicings. Luft Hansa had good service from Diesel engines for over 300 hours; with the petrol engine he thought it was 200 hours.

E. L. CARLISLE (Air Registration Board, *Associate Fellow*): He could not help thinking that the maintenance problems of this engine would outweigh the saving in fuel consumption and cost. The matching of the maintenance checks of the Diesel engine, and of the compressor and turbine side, might be difficult. It would seem that perhaps a new type of Licensed Aircraft Engineer would appear, *i.e.* a combination of piston Diesel and jet engineer.

It would be very interesting to see a number of these engines in actual service when the various debatable aspects could be demonstrated; he would like to see a trial installation of a Nomad engined aircraft handed over to one of the airlines for freight operation.

B. S. SHENSTONE (British European Airways, *Fellow*): Reference was made to the low specific consumption with water injection. Was the weight of the water included in the consumption quoted?

Concerning the reference made to licensing, he did not want to be concerned with special licences. All their aircraft were very complicated, and if they tried to establish licences for everything they would have a large number of specially licensed people. They wanted the Air Registration Board to approve those engaged on the engineering side in the airlines as responsible people who were able to get on with the job and approve the organisation rather than individuals. If it fell down on the job, then was the time for A.R.B. to jump.

Some very interesting remarks had been made about freighters. He had heard somewhere that freighting would be left to the independent operators, and he would be very pleased to hear what those operators had to say about that problem.

AIR COMMODORE F. R. BANKS: He thought that Major Gould must have been misinformed on the German Luft Hansa. He had a good many contacts with Luft Hansa, and could assure him that that airline ran mainly with petrol (gasoline) engines and not Diesels. They had some JU 86's, but not many in regular passenger service. Before the war, he was in a JU 86 when it met with an accident and the engine caught fire. There was not that devastating conflagration such as occurred with petrol, but it went on fire and they had to get out quickly.

SIR SYDNEY CAMM: Of considerable interest was the fact that the carrying of air freight did not necessarily necessitate travel at extreme speeds. It seemed to him that they might not have given sufficient thought to that branch of aviation in Great Britain.

The paper was very interesting, particularly in view of the very low specific consumption claimed. In these days, when it was necessary to make the aircraft smaller and at the same time to provide greater volume to carry

the extra fuel required for the turbo-jet engine, that appealed to him very much indeed.

He would like to thank the lecturer for his most interesting compilation of information concerning this compound engine.

Written contributions from members of the New Zealand Division of the Society:—

H. T. ADAMS (Senior Lecturer in Mechanical Engineering, Canterbury University College, New Zealand): It was interesting to note a similarity between the development of marine and aircraft engines as exemplified by this compound arrangement. The combination of a triple expansion engine with a low pressure turbine was a parallel, and in both cases the arrangement suited the state of development of the turbine. If a simple turbine cycle could be used between the same working limits (2,200 lb./in.^{2} abs. and 2,500°K) the fuel consumption should be in the region of 0·1 lb. fuel (S.H.P.) (hour). Nevertheless, that being quite out of the question at the present time, the economy effected by compounding was very marked. Some of the mechanical features were interesting departures from usual practice, in particular the connecting rod bearings. Those appeared to show a marked advance in design.

W. H. DUNN (Chief Performance and Power Plants Engineer, Civil Aviation Branch, Air Department, New Zealand): This type of power unit should have a big future in the field of air freight where the operating cost per ton mile was the main consideration. It was well shown in the paper from the point of view of thermal efficiency that this type of power unit combined the advantages of both the reciprocating engine and the compressor turbine unit. The manufacturers were also to be congratulated on designing a power unit with such a high thermal efficiency for such a low specific weight ratio. The method employed for gearing the two power units was most ingenious. Had many mechanical difficulties been encountered with the variable speed gear and what was the life of this unit compared with the rest of the engine? Also, what was the reason for the large flanged opening at the rear of the engine in the top of the variable speed gear chamber?

T. T. N. COLERIDGE (Chief Technical Adviser, The Shell Company of New Zealand): Mr. Chatterton's paper gave a very clear account of this type of aircraft's power unit and in particular his explanation of the basic reasoning behind the derivation of the particular compounding arrangements was exceptionally clear and concise. He noticed that the engine was stated to be able to use Diesel fuel, but it would seem to him that the conventional readily obtained Diesel fuels would not be directly suitable for aviation use. Presumably a distillate such as automotive gas oil was intended by the term "Diesel Fuel" and that was an appreciably higher quality than the heavier Diesel fuels used in, say, railway locomotive Diesel engines of comparable cylinder size, Automotive gas oil even would not be suitable for aviation purposes on account of the relatively high pour point of these fuels, unless there was provision for heating of the aircraft fuel tanks. That would occasion some loss of payload and also be an added complication. Aviation Diesel fuels had been manufactured in the past but they were of exceptional quality and possibly the same availability advantage might not apply.

It would be interesting to know how complete was the combustion of the fuel. The two-stroke Diesel engine normally was not exceptionally good in this respect and was liable to cause trouble from build up of deposits in exhaust ports. Although in this engine there was ample excess air that in itself was not necessarily a safeguard against incomplete combustion, as such two-stroke Diesel engines were not uncommonly just as troublesome with regard to deposits under light load conditions. Presumably with an engine of this nature the build up of deposits on the exhaust side could be most objectionable in that the turbine efficiency might be badly affected. In this connection it would be interesting to know what service life between overhauls had so far been obtained or was expected. An indication from the author of what limited such overhaul life would be extremely interesting.

The Velox Boiler was a close parallel to this compound engine in that the main combustion chamber of this boiler was under pressure, in this case some 35 lb. in^2. This combustion chamber pressure was maintained by a multi-stage compressor driven by the gas turbine which received its energy from the flue gas exhausting from the steam boiler. This particular type of boiler was in fact fairly sensitive to fuel quality, even though it burned fuel at the rate of as much as 3½ tons per hour. Small domestic type boilers of exactly similar principle, but running on much lighter fuels, were similarly noticeably sensitive to fuel quality and from those two analogies one would expect that the compound Diesel engine might similarly be sensitive to changes of fuel quality such as hydrogen/carbon ratio, volatility, viscosity and ignition quality to a greater degree than a conventional Diesel engine.

He thought this engine appeared to have a very promising future, but with its high degree of complexity it was permissible to examine fairly closely the advantages claimed. Undoubtedly the specific fuel consumption was a most important attraction, but for a greatly increased complexity there was no real advantage in this respect over aircraft Diesel engines made nearly 20 years ago and those had completely disappeared. Although admittedly the total power output was very much greater it appeared to him that the advantage in this engine was the low specific fuel consumption in conjunction with the extremely flat shape of all the curves in Figs. 19 and 22.

It would be interesting to know approximately the range of speed at which the turbine compressor unit operated, as he could not find this recorded in the paper. Was it necessary to use a different lubricating oil for the gear train and infinitely variable gear unit, as distinct from the lubricating oil for the Diesel engine?

Mr. Chatterton's Reply

AIR COMMODORE BANKS: It was his personal hope that Sir Harry Ricardo would be present that evening, for he did valuable work in pointing out the possibilities of the Compound Engine for aircraft use. Sir Harry also did a lot of work on single cylinder units side by side with Napiers while the difficulties connected with the piston engine were being explored.

The idea of compounding was far from new and, in a simple form, was suggested by Dr. Buchi about 1902, but its practical application had only been made possible by advances in gas turbine technique, and the most suitable form of it for aircraft use demonstrated in the Nomad.

The variable gear box was originally designed for, and built into, a motor car and the thing that convinced him of its serviceability before he had the courage to introduce it into the Nomad was, that two of the German "people's cars" were equipped with these gears before the last war, and both of them ran for many thousands of miles without giving trouble. That seemed to him to be an indication that they were satisfactory.

The idea that higher specific fuel consumptions were beneficial was a curious one, but he still did not think it was sound engineering. Certainly the conditions existing in the example quoted would require very careful examination before it could be taken as indicating that engine builders should strive for higher fuel consumptions.

The "effective" compression ratios quoted in the paper were calculated from the point of port closing.

MR. ALCOCK: It had been very interesting to see the illustration of the Ricardo horizontally opposed engine design. This was very similar to the type of cylinder they were running at Napier's and at Ricardo's in association in the early days, and it was at quite a late date that at Napier's they changed to the alternative system of scavenging. With the type of scavenging now used, the performance was improved and the inlet and exhaust manifolds were on one side of the cylinder only, which simplified things and saved a lot of weight.

Referring to maximum cylinder pressures, there were obvious advantages from a performance point of view in operating as high as practical considerations would permit, and the ability to run with the pressures quoted was a direct result of the small end bearing development which had been referred to in the paper. The ring wear had also responded to developments in piston design, particularly in respect of cooling and the ring life was satisfactory for aircraft use.

The grooves shown under the piston crown were not oil grooves but were put in to reduce contact area between the steel crown and the aluminium body. Oil cooling was restricted to the part of the piston behind the ring grooves. He was sorry he had had to cut the description of the piston out of the paper, because it was quite an interesting development which had made a considerable improvement in piston cooling. There was a series of drilled holes from the annular chamber behind the rings which allowed the oil to be shaken down by the piston movement into the skirt, and this acted as a very efficient heat transporter which kept the ring temperatures down.

Recent experience had shown that the sparks were required only for starting purposes and were not used when the engine was idling.

The maximum power going through the variable gear was just under 200 h.p. and the slip varied over the operating range from 2 per cent. up to about 5 per cent. Just how the load was transmitted at the contact surfaces he would not like to say but they knew that it did respond, with a given end load, to the lubricating conditions. If they gave it too little oil it did not like it, neither did it like too much; there was one condition of lubrication which it appeared to like and at which it transmitted load with high efficiency and very small slip. At present, over the whole range of varying operating conditions, there was a constant loss of about 20 h.p. but he thought that would change with further development towards a more constant value of mechanical efficiency.

DR. MOULT: The heat losses to coolant at cruising conditions were about 14 per cent. of the total heat released from the fuel, which was quite a low figure for coolant loss whether for a liquid- or an air-cooled motor. It was also interesting to record that the radiator in a Nomad installation was smaller than that for any other liquid-cooled engine of equivalent total power, for the radiator had only to deal with the Diesel contribution which was only a percentage of the total power output.

To carry Dr. Moult's argument on engine weights to its logical conclusion, it was not only the weight of the installed power plant which should be taken in making weight comparisons, but the weight of the power plant plus the weight of fuel required for a flight of given duration, and it was on this basis that the Nomad installation showed to advantage. It was certainly not true that the turbo-charged petrol engine, as exemplified by the Wright Turbo-Compound, could compete with the Nomad on the basis of fuel economy.

As Dr. Moult pointed out, the best consumption of the turbo-charged petrol engine was at least 15 per cent. higher than that of the Nomad, and whereas the Nomad minimum consumptions were maintained over a very wide range of engine powers and flight conditions, the minimum figures for the petrol engine were achieved only at one engine power, at one altitude and one flight speed. There was a further difference in the cost of the fuels involved, the piston engine using the most expensive high octane fuel and the Nomad a much cheaper Diesel fuel, although the major saving of the Nomad arose from its lower consumption and not from the difference in fuel cost.

This would apply equally to the hypothetical Centaurus engine fitted with an exhaust turbine and the one simplified comparison made by Dr. Moult was not valid in the practical case, if economy of operation were to be the basis of comparison.

No trouble had been experienced with transmission of torsional vibration from the Diesel engine to the compressor or turbine. It might be that the discs of the variable gear had provided some damping, which would be highly providential.

The rate of acceleration of the engine was as rapid as that of any other piston engine, probably because the compressor was geared to the crankshaft and not gas-coupled, as in the turbo-blower case.

MAJOR GOULD: Needless to say, he agreed entirely with Major Gould on the economical superiority of the Nomad engine! It was certain that once they considered seriously, air freighting as a business, they just had to think in terms of fuel consumption and economy of operation and, under those conditions, the virtues of the Nomad engine became apparent. So long as they thought in military terms, where speed and effectiveness of military operations were the only factors that mattered, they would have engines not primarily suited for economical commercial activities.

When he was in America recently, an American said to him that air freighting was not worth its salt until they could consider transporting coal by air if necessary. That was an exaggeration to illustrate a point of view but, until they adopted such a mental attitude towards air transport they were not really in the air freighting business.

The Nomad was designed to give 1,000 hours of operation between overhauls; all the stress figures and bearing loads were based on that figure. They had not demonstrated in service yet, but hoped to do so in the near future. In common with all Diesel engines, the maintenance requirements were going to be considerably less than for petrol engines. It was common experience that the maintenance of fuel injection equipment was much easier and cheaper than the maintenance of carburettors and electrical equipment in the spark ignition engine, and he would therefore expect this engine to be cheap and easy to maintain.

MR. CARLISLE: The real answer to Mr. Carlisle's point would only be given by practical demonstration but he certainly wished to quarrel with his contention that maintenance costs on the Nomad would outweigh the other savings.

It must be remembered that the Nomad turbine operated at much lower gas temperatures than in the normal turbine engine so that the turbine and compressor should easily have an overhaul life of 1,000 hours for which the Diesel engine component had been designed. The "matching" difficulty therefore should not exist and the difficulties should be less than those experienced on combustion cans of normal turbines.

MR. SHENSTONE: The water consumption was not included in the specific consumption figures which referred only to fuel consumption.

MR. DUNN: The only mechanical difficulties experienced with variable speed gear arose during manufacture of the taper discs. To keep weight down, the thickness of these was reduced to a minimum and some trouble was experienced with cracking during hardening or grinding. Those difficulties had now been overcome by improved manufacturing technique.

Practical experience indicated that the gear should not require attention for at least the 1,000 hour overhaul life of the engine.

The flanged opening in the variable gear casing was the engine breather.

MR. COLERIDGE: Most of the running on Nomad engines had been done on Aviation Kerosine and on Gas Oil. Contrary to the inferences drawn from the Velox Boiler example, the engine was peculiarly insensitive to fuel changes, and would run equally well on "wide cut" gasoline or on so-called "Class B" Diesel fuels. The problem of fuel heating was not difficult, as the engine was provided with a circulating type fuel system, in which the engine consumed only a small proportion of the total fuel circulated. Arrangements could, therefore, be made easily for the appropriate amount of heating to be applied to the fuel returning to the tank with no great sacrifice in weight or complexity.

There was some carbon deposit in the exhaust ports when the engine was run for prolonged periods on light loads, but this did not build up to a dangerous extent and was completely burned off when the engine was put on load.

The life of the engine between overhauls was anticipated to be 1,000 hours and this was determined by the piston ring conditions. That period would be extended with further running experience.

Mr. Coleridge was quite wrong when he stated that there was little advantage for the Nomad as compared with normal Diesel engines and it was true to say that, at the present time, no Diesel engine could compete against *any* of the alternative engines now available. The reasons for this lay in the weight and bulk of the Diesel engine, the comparison being indicated by the figures in Table I, which showed that the Junkers engine, which was a very good example of the Diesel motor, produced only 36 h.p. per litre of cylinder capacity against the potential 96·5 of the Nomad, while the specific weight of the Junkers was 1·91 lb. per h.p., as compared with 0·959 for the Nomad.

Apart from this, there was the great advantage to which Mr. Coleridge drew attention, that the extremely flat power and consumption curves of the Nomad provided a flexibility which gave overall economy in flight of an order not possible with any other engine, and, certainly not with the normal Diesel.

The range of speeds for the turbo-compressor set given by the variable gear combination was approximately 1·5/1, and the same oil was used throughout the engine.

Computation of Initial Buckling Stress for Sheet-Stiffener Combinations

by

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1. Introduction

The issue of the Royal Aeronautical Society Structures Data Sheets 02.01.28 to 37* prompts the publication of a short survey of the theory on which these sheets are based and of the manner in which they may be applied. To save the need to refer to original sources the theory is developed from first principles; but for brevity the application is illustrated only by one simple example. Other more elaborate applications are illustrated by the example data sheets themselves. A recent paper by Chilver[2] covers the same ground from the mathematical point of view and the purpose of the present paper is to illustrate the practical application of the method to familiar problems in the computation of initial buckling stress for sheet-stiffener combinations.

Notation

x, y, z	Cartesian co-ordinates
u, v, w	displacements
e_{xx}, e_{yy}, e_{zz} or e_x and e_y	direct strains
e_{yz}, e_{zx}, e_{xy} or ϕ	shear strains
$\overline{xx}, \overline{yy}, \overline{zz}$ or f_x and f_y	direct stresses
$\overline{yz}, \overline{zx}, \overline{xy}$ or q	shear stresses
E	Young's modulus
G	shear modulus
σ	Poisson's ratio
$E' =$	$E/(1-\sigma^2) = 2G/(1-\sigma)$
U	strain energy
U_d	strain energy associated with distortion
U_w	strain energy associated with warping
t	thickness of sheet
b	width of plate
λ or λ'	half wavelength of warping deformation
f_c	compressive stress
f_0	buckling stress for plate with edges simply supported
Y	function of y
α_1, α_2, P, Q	functions of (f_c/f_0) and (b/λ)
r, s	integers
μ_1, μ_2, μ_3	rotational stiffnesses.

2. Derivation of Basic Formula for Thin Plates

The strain energy U stored in an isotropic body may be written in the form

$$U = \frac{G}{3}\iiint \left\{ \frac{1+\sigma}{1-2\sigma}(e_{xx}+e_{yy}+e_{zz})^2 + (e_{yy}-e_{zz})^2 + (e_{zz}-e_{xx})^2 + (e_{xx}-e_{yy})^2 + \frac{3}{2}(e_{yz}^2+e_{zx}^2+e_{xy}^2) \right\} dx\,dy\,dz. \quad (1)$$

*These Data Sheets will be issued, with others, by the end of this year.—Ed.

G is the shear modulus and σ the Poisson's ratio of the material; e_{xx}, e_{yy} and e_{zz} are the direct strains and e_{yz}, e_{zx} and e_{xy} are the shear strains parallel to Cartesian axes $Oxyz$ at the point (x, y, z).

In a thin sheet the stress $\overline{zz}$ normal to the sheet surface is zero at both surfaces and it is a reasonable approximation to assume $\overline{zz}=0$ everywhere. In that case

$$e_{zz} = -\frac{\sigma}{1-\sigma}(e_{xx}+e_{yy})$$

and by substitution in formula (1)

$$U = \frac{1}{4}E'\iiint [(1+\sigma)(e_{xx}+e_{yy})^2 + (1-\sigma)\{(e_{xx}-e_{yy})^2 + e_{xy}^2 + e_{yz}^2 + e_{zx}^2\}]\,dx\,dy\,dz$$

where $$E' = \frac{E}{1-\sigma^2} = \frac{2G}{1-\sigma}.$$

Moreover the shear stresses $\overline{yz}$ and $\overline{zx}$ are zero at both surfaces of the sheet and since $e_{yz} = \overline{yz}/G$, and so on, so also are e_{yz} and e_{zx}. Therefore it is reasonable to assume e_{yz} and $e_{zx}=0$ everywhere, so that the strain energy reduces to

$$U = \frac{1}{4}E'\iiint [(1+\sigma)(e_{xx}+e_{yy})^2 + (1-\sigma)\{(e_{xx}-e_{yy})^2 + e_{xy}^2\}]\,dx\,dy\,dz. \quad (2)$$

If we take the plane $z=0$ as the middle surface of the (flat) sheet, and if the displacement of the point (x, y) in this middle surface is (u, v, w), the displacement of the point (x, y, z) is $(u+zw_x, v+zw_y, w)$* because it has been assumed that there is no shear strain through the sheet thickness. Then in the plane z the strains are

$$\left.\begin{aligned} e_{xx} &= u_x + \tfrac{1}{2}w_x^2 + zw_{xx} \\ e_{yy} &= v_y + \tfrac{1}{2}w_y^2 + zw_{yy} \\ e_{xy} &= u_y + v_x + w_x w_y + 2zw_{xy} \end{aligned}\right\}. \quad (3)$$

the terms $\frac{1}{2}w_x^2$, $\frac{1}{2}w_y^2$ and $w_x w_y$ being included to cover cases of buckling, when these terms may be comparable with u_x, v_y and $u_y + v_x$.

On substitution of the forms (3) in the formula (2) and integration with respect to z between the limits $\pm(t/2)$, where t is the thickness of the sheet, the strain energy U divides into two parts

$$U_d = \frac{1}{4}E't\iint [(1+\sigma)(u_x+v_y+\tfrac{1}{2}w_x^2+\tfrac{1}{2}w_y^2)^2 + (1-\sigma)\{u_x-v_y+\tfrac{1}{2}w_x^2-\tfrac{1}{2}w_y^2)^2 + (u_y+v_x+w_x w_y)^2\}]\,dx\,dy \quad (4a)$$

and

$$U_w = \frac{1}{48}E't^3\iint [(1+\sigma)(w_{xx}+w_{yy})^2 + (1-\sigma)\{w_{xx}-w_{yy})^2 + 4w_{xy}^2\}]\,dx\,dy$$

*Note: Suffixes x and y, when attached to u, v and w denote partial differentiation, *e.g.* $u_x = \partial u/\partial x$, $w_{xyy} = \partial^3 w/\partial x \partial y^2$.

or

$$\frac{1}{24}E't^3\iint\{(w_{xx}+w_{yy})^2+2(1-\sigma)(w_{xy}{}^2-w_{xx}w_{yy})\}\,dx\,dy \quad . \quad . \quad . \quad (4b)$$

If $u_x=e_x$, $v_y=e_y$ and $u_y+v_x=\phi$ and if e_x e_y and ϕ are constant throughout the sheet, the expression for U_d, in so far as it depends on w, reduces to

$$\tfrac{1}{2}E't\iint\{(e_x+\sigma e_y)w_x{}^2+(e_y+\sigma e_x)w_y{}^2+(1-\sigma)\phi w_x w_y+ + \text{terms of order } w^4\}\,dx\,dy \quad . \quad . \quad (5)$$

or, disregarding the terms in w^4 which are negligible at the initiation of buckling,

$$U_d=\text{constant}+\tfrac{1}{2}t\iint(f_x w_x{}^2+f_y w_y{}^2+2qw_x w_y)\,dx\,dy \quad (6)$$

where $f_x=E'(e_x+\sigma e_y)$, $f_y=E'(e_y+\sigma e_x)$ and $q=G\phi=\frac{1}{2}(1-\sigma)E'\phi$ are the uniform stresses to which the sheet is subjected before buckling.

The total strain energy associated with lateral deflection (w) on buckling is then the sum of U_d and U_w as defined in formulae (4*b*) and (6). This formula could have been quoted from Ref. 1, Chapter VIII, Article 60, p. 306, formula (183), but the complete derivation from the basic formula (1) has been rehearsed in order to emphasise the assumptions and approximations on which the final form is founded.

3. The Differential Equation for Lateral Deflection

The variation of the total energy

$$\frac{1}{24}E't^3\iint\{(w_{xx}+w_{yy})^2+2(1-\sigma)(w_{xy}{}^2-w_{xx}w_{yy})\}dx\,dy+ + \tfrac{1}{2}t\iint(f_x w_x{}^2+f_y w_y{}^2+2qw_x w_y)dx\,dy \quad . \quad (7)$$

with respect to w must be zero. This condition may be used to derive the differential equation governing lateral deflection.

For instance,

$$\delta\iint\tfrac{1}{2}w_{xx}{}^2\,dx\,dy=\iint w_{xx}\delta(w_{xx})\,dx\,dy$$
$$=\iint w_{xx}(\delta w)_{xx}\,dx\,dy$$
$$=\int[w_{xx}\delta w_x-w_{xxx}\delta w]\,dy+\iint w_{xxxx}\delta w\,dx\,dy.$$

Treating the other terms in (7) similarly and collecting all the terms under the double integral, the variation of (7) yields

$$t\iint\left\{\frac{1}{12}E't^2(w_{xxxx}+2w_{xxyy}+w_{yyyy})-\right.$$
$$\left.-f_x w_{xx}-f_y w_{yy}-2qw_{xy}\right\}\delta w\,dx\,dy \quad (8)$$

and for equilibrium the integrand must be zero (so that the energy (7) shall not be altered by the arbitrary (small) variation of w, δw). This formula is equivalent to formula (175) of Ref. 1.

The single integrals, which have been disregarded, relate to boundary conditions; for instance the complete term involving δw_x is

$$\int[\{w_{xx}+\sigma w_{yy}\}\delta w_x]\,dy.$$

Therefore at any edge parallel to Oy, at which w_x may be varied arbitrarily, $w_{xx}+\sigma w_{yy}=0$. The expression $w_{xx}+\sigma w_{yy}$ is proportional to the bending moment applied at the edge of the sheet, and the result derived simply means that if the edge is completely free to rotate (δw_x unrestricted) the edge is free from applied bending moment. Similarly if δw_x is zero at an edge, that edge is clamped and the bending moment at the edge represented by $w_{xx}+\sigma w_{yy}$ is free to assume any value.

Application of minimum energy principles thus provides for equilibrium at all parts of the sheet including its edges, but for the present purpose it is more convenient to use the differential equation alone and to consider the boundary conditions separately.*

4. Lateral Deflection of a Plate under Uniaxial Compression

The lateral deflection w of a plate under uniaxial compression $f_x=-f_c$ (with $f_y=0$ and $q=0$) must satisfy the differential equation

$$\frac{1}{12}E't^2(w_{xxxx}+2w_{xxyy}+w_{yyyy})+f_c w_{xx}=0. \quad . \quad (9)$$

where f_c is the uniform axial compressive stress. (*cf.* Ref. 1, Art. 63 formula (a)).

If $w=Y\sin(\pi x/\lambda)$, the function Y of y must satisfy the differential equation

$$Y_4-2(\pi/\lambda)^2Y_2+(\pi/\lambda)^2\{(\pi/\lambda)^2-(4\pi^2f_c/f_0b^2)\}Y=0$$

where $f_0=\frac{1}{3}\pi^2E'(t/b)^2$, b is the width of the plate,

and Y_2 stands for $\partial^2Y/\partial y^2$ etc.

A solution of this equation is

$$Y=Ce^{(\pi y/b)\alpha} \quad . \quad . \quad . \quad (10)$$

provided that

$$\alpha^4-2(b/\lambda)^2\alpha^2+(b/\lambda)^2\{(b/\lambda)^2-4(f_c/f_0)\}=0.$$

whence $$\alpha^2=(b/\lambda)^2\pm2(b/\lambda)(f_c/f_0)^{\frac{1}{2}} \quad . \quad . \quad (11)$$

(*cf.* Ref. 1. 1 Art. 63 formula (d))

The formula (10) includes four arbitrary constants, one for each of the four roots $\pm\alpha_1$ and $\pm\alpha_2$ of formula

*Treatment of the terms in the single integrals which involve δw involves difficulty with regard to the integration of the term in $w_{xy}{}^2$. This difficulty arises from the failure in the basic analysis to recognise the existence of shear stresses normal to the sheet surface. No perfectly consistent solution in accord with this neglect is possible; but at a free edge which is, of course, free from both shear loading normal to the sheet edge and also from torsion applied by differential shear loadings parallel to the sheet surface, both types of loading may be grouped together and the conditions to be satisfied are $w_{xxx}+(2-\sigma)w_{yyy}=0$ at an edge parallel to Oy or $w_{yyy}+(2-\sigma)w_{xxy}=0$ at an edge parallel to Ox. On the other hand, within the sheet the two shear loadings are proportional to $w_{xxx}+\sigma w_{xyy}$ and $w_{yyy}+\sigma w_{xxy}$, while the loadings $2(1-\sigma)w_{xyy}$ and $2(1-\sigma)w_{xxy}$ are transmitted by torsion, that is by shear stresses parallel to the sheet surface.

(11), and adjustment of the values of these constants to the boundary conditions, two at each edge parallel to Ox, completes the solution. So far the present analysis follows Timoshenko precisely, but in the development which follows a different procedure is adopted.

5. Effective Stiffnesses to Edge Rotation of Parallel Strips under Axial Compression

The formula (10) may be rewritten in the form

$$Y = A\cosh\alpha_1(\pi y/b) + B\cosh\alpha_2(\pi y/b) + C\sinh\alpha_1(\pi y/b) + D\sinh\alpha_2(\pi y/b) \quad (12)$$

where the axis Oy is now taken in the centre of the width b of the strip. The first pair of terms represents deformation symmetrical about this mid-line and the second pair represents anti-symmetrical deformation; these two cases will be treated separately.

If $w=0$ at both edges,

$$A\cosh(\pi\alpha_1/2) + B\cosh(\pi\alpha_2/2) = 0;$$

the rotation at these edges is

$$(w_y)_{y=\pm b/2} = (Y_y)_{y=\pm b/2}\sin(x\pi/\lambda) = \pm(\pi/b)\{\alpha_1 A\sinh(\pi\alpha_1/2) + \alpha_2 B\sinh(\pi\alpha_2/2)\}\sin(\pi x/\lambda)$$

and the bending moment per unit length of edge is

$$\frac{1}{12}E't^3(w_{yy})_{y=\pm b/2} = \frac{1}{12}E't^3(Y_{yy})_{y=\pm b/2}\sin(\pi x/\lambda) = \frac{1}{12}(\pi/b)^2E't^3\{\alpha_1^2 A\cosh(\pi\alpha_1/2) + \alpha_2^2 B\cosh(\pi\alpha_2/2)\}\sin(\pi x/\lambda).$$

The effective "stiffness" to rotation of the edge, expressed as the ratio of the local value of bending moment per unit length of edge to the local rotation is then

$$\frac{1}{12}E't^3(\pi/b)(\alpha_1^2 - \alpha_2^2)/\{\alpha_1\tanh(\pi\alpha_1/2) - \alpha_2\tanh(\pi\alpha_2/2)\}$$

which is preferably written in the form

$$\mu_2 = (E't^3/3b)\times(\pi/4)(\alpha_1^2 - \alpha_2^2)/\{\alpha_1\tanh(\pi\alpha_1/2) - \alpha_2\tanh(\pi\alpha_2/2)\} \quad (13)$$

where $\alpha_1^2 = (b/\lambda)^2 + 2(b/\lambda)(f_c/f_0)^{\frac{1}{2}}$ and is always positive and $\alpha_2^2 = (b/\lambda)^2 - 2(b/\lambda)(f_c/f_0)^{\frac{1}{2}}$, and is negative if $f_c/f_0 > b^2/4\lambda^2$.

The function (14) is represented in R.Ae.S. Structures Data Sheets 02.01.31 and 32 as a system of curves relating $\mu_2/\{E't^3/(3b)\}$ to b/λ for a series of values of f_c/f_0.

The anti-symmetric terms in formula (12) represent a condition in which both edges of the strip rotate in the same sense under equal bending moments distributed along each edge also acting in the same sense.* For this case if $w=0$ at each edge,

$$C\sinh(\pi\alpha_1/2) + D\sinh(\pi\alpha_2/2) = 0;$$

the rotation at each edge is

$$(\pi/b)\{\alpha_1 C\cosh(\pi\alpha_1/2) + \alpha_2 D\cosh(\pi\alpha_2/2)\}\sin(\pi x/\lambda);$$

and the applied bending moment per unit length of edge is

$$\frac{1}{12}E't^3(\pi/b)^2\{\alpha_1^2 C\sinh(\pi\alpha_1/2) + \alpha_2^2 D\sinh(\pi\alpha_2/2)\}.$$

Hence the effective "stiffness" analogous to μ_2 is

$$\mu_3 = (E't^3/3b)\times(\pi/4)(\alpha_1^2 - \alpha_2^2)/\{\alpha_1\coth(\pi\alpha_1/2) - \alpha_2\coth(\pi\alpha_2/2)\} \quad (14)$$

The function (14) is represented in R.Ae.S. Structures Data Sheet 02.01.33 as a system of curves relating $\mu_3/\{E't^3/(3b)\}$ to b/λ for a series of values of f_c/f_0.

A third case of technical importance is that of an outstanding flange with its remote edge entirely unrestrained. For this case it is necessary to adjust the complete formula (12) to the conditions $w=0$ at the inner edge and $w_{yy} + \sigma w_{xx} = 0$ and $w_{yyy} + (2-\sigma)w_{xxy} = 0$ at the free edge. Then the ratios of the four constants A, B, C and D are defined and the effective stiffness to rotation about the inner edge is

$$\mu_1 = (E't^3/3b)\times(\pi/4)\{(\alpha_1^2 - \alpha_2^2)/(\alpha_1\alpha_2)\}\times \frac{\{\alpha_2 Q^2\sinh\pi\alpha_1\cosh\pi\alpha_2 - \alpha_1 P^2\sinh\pi\alpha_2\cosh\pi\alpha_1\}}{\{2PQ + (P^2+Q^2)\cosh\pi\alpha_1\cosh\pi\alpha_2\} - (\alpha_1^2 P^2 + \alpha_2^2 Q^2)\sinh\pi\alpha_1\sin} \quad (15)$$

where α_1 and α_2 have the same meanings as before and

$$P = 2(f_c/f_0)^{\frac{1}{2}} - (1-\sigma)(b/\lambda)$$

and

$$Q = 2(f_c/f_0)^{\frac{1}{2}} + (1-\sigma)(b/\lambda).$$

(*cf.* Ref. 3, p. 5, Formula for $S'''/(D/b)$)

The function (15) is represented in R.Ae.S. Structures Data Sheets 02.01.29 and 30 as a system of curves relating $\mu_1/\{E't^3/3b)\}$ to b/λ for a series of values of f_c/f_0.

6 Application of the Data Sheets

By reference to formula (7) it will be seen that for a long structure, provided that f_x, f_y and q and the limits of integration for y are independent of x, deformation having a half wavelength λ has no interaction with deformation having any different half wavelength λ'; this is because

$$\int_0^\infty \sin(\pi x/\lambda)\sin(\pi x/\lambda')dx = 0 \text{ unless } \lambda = \lambda'.$$

For a structure of finite length a, the cognate condition

$$\int_0^a \sin(r\pi x/a)\sin(s\pi x/a)\,dx = 0 \text{ for } r \neq s \text{ and } r \text{ and } s \text{ both integers}$$

is slightly more restricted in that $\lambda = a/r$ and $\lambda' = a/s$ must both be submultiples of a; however this condition is usually implicit in problems relating to structures of limited length.

This characterisation by wavelength, which is the basis of the Data Sheets 02.01.29-33 representing the

*Since uniform bending moment is represented by equal and *opposite* moments at the two edges, the applied bending moments are in this case "hogging" on one side and "sagging" on the other.

properties of flat plates under end load, is also true for *any* structure of uniform cross section under end load; moreover, although the end loading must not vary down the length of the structure it need not be constant over the whole cross section*.

In many typical aircraft structures the cross section consists of several flat plates joined edge to edge. Wherever two or more flats meet at an angle it is reasonable under certain restrictions, which will be noted in Section 7 below, to assume that the line of junction remains straight, because any deflection of the line would necessitate bending of one or more flats in its own plane and that is usually strongly resisted. Then the whole system of possible deformations is representable by the angles of rotation θ_r about each of the r lines of junctions in the complete cross section, but each θ represents a rotation $\theta \sin(\pi x/\lambda)$ varying sinusoidally down the length of the structure, each with the common half wavelength λ. For a flat between two lines of junction at which the rotations are θ_r and θ_s in the same sense, the deformation may be regarded as composed of $\frac{1}{2}(\theta_r - \theta_s)$ of type 2, for which the effective stiffness is represented by μ_2 in Section 5 and Data Sheets 02.01.31 and 32, and $\frac{1}{2}(\theta_r + \theta_s)$ of type 3, for which the effective stiffness is represented by μ_3 in Section 5 and Data Sheet 02.01.33. Thus the moments applied at the two edges are the products with $\sin(\pi x/\lambda)$ of

$$\left.\begin{aligned} &\tfrac{1}{2}(\mu_2+\mu_3)\theta_r + \tfrac{1}{2}(\mu_3-\mu_2)\theta_s \text{ at the edge } r \\ \text{and}\quad &\tfrac{1}{2}(\mu_3-\mu_2)\theta_r + \tfrac{1}{2}(\mu_2+\mu_3)\theta_s \text{ at the edge } s \end{aligned}\right\} \qquad (16)$$

both moments being the same sense as that of θ_r and θ_s. For a flat having one edge free the moment at the single line of junction is the product of $\sin(\pi x/\lambda)$ with μ_1 as represented in Data Sheets 02.01.29 and 30. In actual computation it is convenient to designate each individual plate by a capital letter A, B, C, and so on, and to use A_1 to denote the value of μ_1 for the plate A, and similarly for A_2 and A_3.

Proceeding in this way it is possible to represent the total moment about the line of junction r as a linear function of the rotation θ_r about this line and of the rotations θ_s, θ_q, and so on about all adjacent lines of junction to which the r-line is joined by individual flats. This moment must be equated to the moment actually applied about the r-line and the set of simultaneous equations so defined determine all the θ's in terms of the applied moments as functions of the half wavelength λ and the end loading f_x which affect the values of the multiplying factors A_1, A_2, and so on.

7. Determination of Buckling Stress

In the entire absence of applied moments about the edge lines, the set of simultaneous equations is homogeneous in θ's and the only solution is $\theta_r = 0$ for all r unless the determinant in the coefficients (composed of A_1, A_2, and so on) itself reduces to zero; in that case only the ratios of the θ's are defined and their absolute magnitudes are unrestricted.

This condition thus represents buckling. The process of computing the initial buckling stress consists then of a search, by trial of all possible values of λ for each of a gradually increasing sequence of f_x*, the lowest value of f_x at which the determinant resulting by elimination of all the θ's has a zero value.

If it were possible to represent f_x in the determinant as an explicit arbitrary parameter, the determinant would have as many roots in f_x as there were individual values of θ. Since, in practice, interest attaches only to the *lowest* root, it is reasonable to attempt by presumption to simplify the determinant by disregard of conditions which relate to the higher roots. For instance, in determining the buckling stress for a plate with simply-supported edges we may anticipate that the rotations will be equal and opposite at the two edges and seek the condition $\mu_2 = 0$ (which of course is afforded first by $f_x = f_0$ at $\lambda = b$, *see* 02.01.31) on the grounds that $\mu_3 = 0$ corresponding to equal rotations in the same sense at both edges *or any component of this mode* must lead to a higher value of f_x for initial buckling. Similarly for a panel stiffened by similar stringers at uniform spacing it is reasonable to guess that the least buckling stress will be associated with equal but opposite rotations about successive stringer webs across the panel width. On the other hand, any variation of stringer size or spacing—or most particularly, variation of effective f_x due to curvature of the panel chordwise in a wing cover—at once invalidates any such presumption, and strictly the full determinant must be examined.

A good illustration is afforded by the case of a thin-walled tube of which the cross section is an equilateral triangle. Since all three sides are equivalent we may ignore the common factor $E't^3/(3b)$ and write for brevity $A = \frac{1}{2}(\mu_2 + \mu_3)$ and $B = \frac{1}{2}(\mu_3 - \mu_2)$; then if the angles of rotation of the three corners are θ_0, θ_1 and θ_2, the three moment equations derived from formula (16) are

$$\left.\begin{aligned} 2A\theta_0 + B\theta_1 + B\theta_2 &= 0 \\ B\theta_0 + 2A\theta_1 + B\theta_2 &= 0 \\ B\theta_0 + B\theta_1 + 2A\theta_2 &= 0 \end{aligned}\right\} \quad . \quad . \quad (17)$$

By elimination of the θ's, the roots are $A + B = 0$, which implies $\theta_0 = \theta_1 = \theta_2$, and $2A - B = 0$ (2 roots), which implies only $\theta_0 + \theta_1 + \theta_2 = 0$. Thus uniform rotation at each corner (which at first sight may seem obvious by symmetry) is associated with the buckling condition $\mu_3 = 0$; whereas *any* system in which the three rotations sum to zero is associated with $3\mu_2 + \mu_3 = 0$ and by reference to 02.01.31 and 33 it will be seen that the latter affords the lower value of f_x. The general formula for a regular polygonal tube with n sides is $\mu_2 + \mu_3 \tan^2(\pi/2n) = 0$ when n is odd or $\mu_2 = 0$ when n is even.

*For example, in the case of a wing cover, allowance may be made for the lower stress in the flanges of the stringers by comparison with the stress in the cover sheet itself; for any component part, such as the stringer web, the equivalent end loading may be taken as the mean value of the compressive stress over the width of the component.

*f_x may differ by constant ratios for individual flats: it here represents one leading value, *e.g.* the stress in the wing cover at the point of greatest wing depth.

Reverting to the case of the triangular tube, since the only condition associated with the buckling criterion $\mu_2+(1/3)\mu_3=0$ is $\theta_0+\theta_1+\theta_2=0$, we may take $\theta_0=0$ and $\theta_1=-\theta_2$. Then by supposing the tube to be cut along the edge at which $\theta_0=0$ and then opened out into a flat plate, it is clear that the buckling criterion $\mu_2+(1/3)\mu_3=0$ applies also to a panel with both its edges clamped and simply-supported along two lines parallel to the edges spaced at one third and two thirds of the whole width of the developed section. It may in fact be shown that the buckling criterion for a panel with clamped edges, divided into n equal plates by $(n-1)$ lines of simple support, is $\mu_2+\mu_3\tan^2(\pi/2n)=0$ for *all* values of n.

For $n=1$ we must have $\mu_2=-$ infinity, and this is the criterion for buckling of an unsupported plate with clamped edges; for $n=2$ the criterion is $\mu_2+\mu_3=0$, and this by (17) is obviously correct, because only θ_1 can differ from zero, and only the second of these three equations has to be satisfied. When $n=4$, the condition reduces to $\mu_2+(3-2\sqrt{2})\mu_3=0$, and by application of Data Sheets 02.01.31 and 33, the critical value of f_x is found to be about $1{\cdot}10\ f_0$ with $\lambda=0{\cdot}96b$; thus if a test panel includes at least three stringers even complete restraint of the edges of the panel against rotation will not increase the plate buckling stress by more than 10 per cent.

8. Limitations on the Use of the Method

The method of analysis based on R.Ae.S. Data Sheets 02.01.29-33 is strictly applicable only when lines of intersection of component flats remain straight. However this does not require that the component flats should actually intersect in a sharp angle; the line of intersection may be taken to be that in which the median planes of the two flats intersect, and the width of each flat is to be taken as the width between its intersection with adjacent flats as so defined. When the junction between two flats is actually a transition radius —as for instance between the web and flange of a rolled sheet stringer—this procedure slightly *underestimates* the resistance of the flat to buckling in respect of the critical value of f_x. In estimating the corresponding load it is usually preferable to multiply by the actual area of section, rather than by the area of section of the idealised structure; although the latter is likely to be closer to the true buckling load, it may in fact exceed it.

In extruded sections having a transition curve at the inside of an angle and a sharper corner on the outside, the true torsional stiffness of the fillet may be appreciable, particularly when one flat has a free edge (outstanding flange). Allowance for this may be made by computing the rotational stiffness $M_T=(\pi/\lambda)^2 GJ$, where $J=\pi/32\ (d^4-t^4)$, d is the diameter of the largest circle which can be inscribed in the angle of the section and t is the mean thickness of the two adjacent flats. (The subtraction of t^4 from d^4 may seldom make any appreciable difference*; but inclusion of this term emphasises the absence of any effect when the angle is in fact sharp).

The most serious limitation on the application of the present method of analysis is the restriction to cases in which the lines of junction of component flats remain straight. In certain cases, such as a flat panel stiffened by top hat stringers, symmetry may debar lateral movement; but in most cases reliance has to be placed on the general argument that each component flat strongly resists translation in its own plane. This resistance is proportional to $(b/\lambda)^4$, so that the argument fails for a narrow strip (b small) and equally for a long wavelength (λ large). The actual criterion is that the whole (stringer) section must resist torsion-bending over the half-wavelength λ very strongly in comparison with the resistance of its stiffest component flat to local deformation of the type represented in μ_1, μ_2 and μ_3. For a typical Z-section the torsion-bending constant Γ is of order $h^5t/100$ (*see* Data Sheet 00.07.02), so that we should have $0{\cdot}01\ h^5t\times E(\pi/\lambda)^4$ large by comparison with $(E't^3/3h)$, or $(h/\lambda)^4>>1/3\ (t/h)^2$. With $h/t=20$, the torsion-bending effect is unimportant so long as $(h/\lambda)>\frac{1}{4}$ say. Since $(h/\lambda)^4$ is compared with $(t/h)^2$, variation of h/t over the usual range (10-30 say) makes no great difference. On the other hand the estimate of Γ (taken from 00.07.02) has been based on a total flange width (including lip if any) of about $\frac{1}{2}h$; if this flange width be halved the value of Γ is reduced to a tenth and the torsion-bending resistance will become comparable with the local buckling resistance when h/λ is not much greater than $\frac{1}{4}$. If the width of a lip or flange is less than one eighth of the width of the flange or web to which it is attached, it is wise to compute the buckling stress as if this lip or flange were not present, and to allow for it only by using the total area of section when computing the buckling load.

The modes of instability which are adequately described by direct application of Data Sheets 02.01.08, and so on, are typified by moderately short wavelengths; that is, in typical constructions by values of λ not greater than one quarter of the panel length. At values of λ comparable with the panel length, torsion and flexure of the stringers will usually play a dominant part; but in the intermediate range of values of λ both torsion and flexure and deformation of cross section may contribute more or less equally. This problem of interaction between the three modes of distortion will be the subject of a further article.

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*For the correction to be appreciable M_T must be comparable with $E't^3/(3b)$, so that $(d/t)^4$ must be of the same order as $(b/t)\ (\lambda/b)^2$. This quantity will usually be of order 100, and in the few exceptional cases in which it may be less than 10, the general method is likely to fail in other respects. As a corollary the correction for torsion of the fillet is unlikely to be worth making unless $d>1{\cdot}5t$.

Air Intake Efficiency*

by

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1. Introduction

The title of this paper is not strictly correct since it is not really concerned with "efficiency" in the accepted sense of the word. It has in the past been considered that the sole duty of an engine air intake is to deliver air to the engine at a high efficiency, that is at a mean total pressure as nearly as possible equal to the aircraft pitot pressure. More recently other considerations have arisen, such as the necessity of avoiding asymmetric flow in twin duct air intakes. These aspects of air intake design have frequently been discussed, for example in Dr. Seddon's lecture† to the Society in December 1951, but the particular subject of this paper has been rather neglected—the velocity distribution of the air delivered to the engine.

It is obviously important that air should be delivered by an air intake not only at high pressure, but also in a manner acceptable to the engine, that is with a reasonably uniform velocity distribution. Although the value of this does not appear in the normal efficiency figure for an intake, it is nevertheless an essential part of its efficient operation. Some attempt will be made to define what is meant by a "reasonably uniform" velocity distribution—in as unbiased a manner as possible, although this paper is inevitably written from the point of view of an engine manufacturer. At any rate it will become clear that there are very cogent reasons why a lot of attention should be paid to this subject.

Typical air intakes

It is first necessary to recall the wide variety of shapes to be found in jet engine air intakes. (This paper is confined to a discussion of air intakes for pure jet engines: some limitation of this sort is essential as otherwise the subject is altogether too large, though of course it is quite legitimate to generalise from some of the particular cases mentioned).

Figure 1 illustrates some of these:—

1. pitot intakes of various lengths, the significant difference between them being that the "bullet" protrudes beyond the entry of the short one,
2. intakes in the leading edge of a highly swept-back wing,
3. divided intakes with entries in the wing roots or on the sides of the fuselage.

Similar intakes are used for twin engine installations also, in which case the individual duct characteristics are similar but any effect of the division between the ducts disappears.

Entry Flow patterns

The wide range of entry conditions over which an intake has to operate must next be considered. Fig. 2 illustrates this range diagrammatically.

During ground running the air approaches from all directions and the flow pattern is as shown in the top diagram; by the end of the take-off run the flow approximates to the second diagram; the next three diagrams show in succession climb, cruise and top speed conditions; and the last shows the flow pattern when the engine is throttled back at high speed. (Nowadays it is more usual to use the inverse of the velocity ratios used in this figure to describe the flow condition, chiefly because when any function is being plotted against velocity ratio the ground running point can conveniently be plotted at a V/v_e of zero instead of infinity).

2. Axial Compressor Characteristics as Affected by Air Intakes

It is the now widespread use of jet engines with axial compressors which has really led to the necessity to study the variation of air velocity across the entry to the engine, and to keep this variation within reasonable bounds.

Most people are familiar with the details of the entry to a typical axial compressor, as shown in Fig. 3. Before the air reaches the compressor blades it has to pass over the fairing over the starter, between the struts supporting the front bearing housing, and through inlet guide

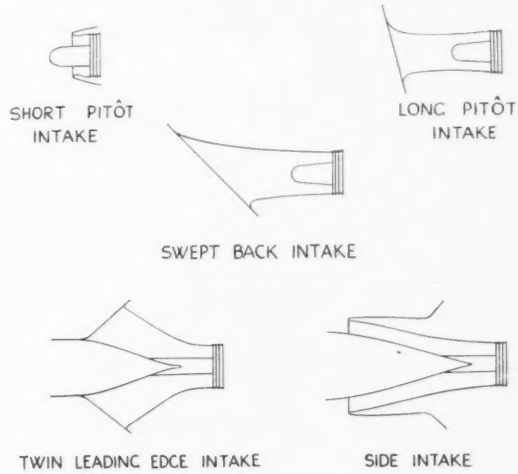

FIGURE 1. Typical engine air intakes.

†*Journal of the Royal Aeronautical Society*, October 1952.

*A Section Lecture read before the Society on 4th February 1954.

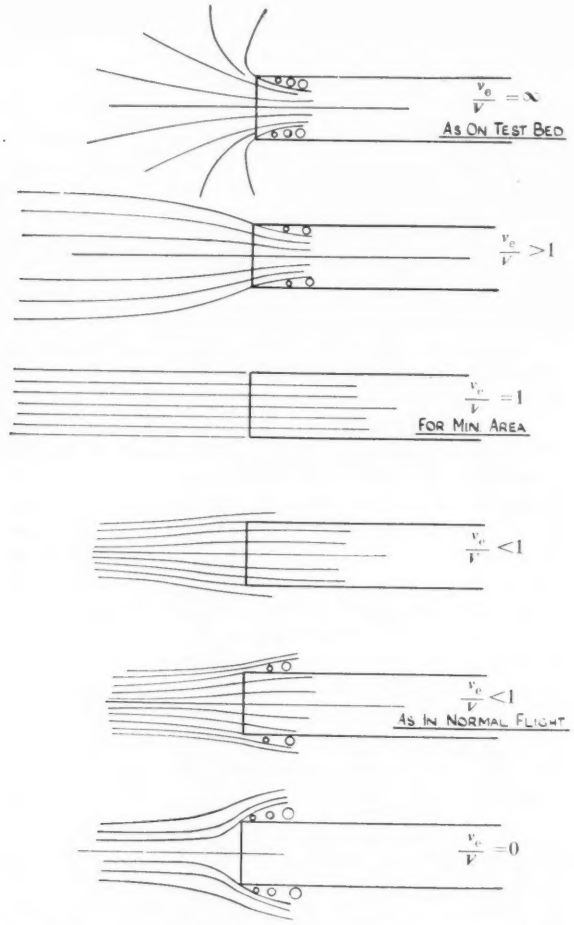

FIGURE 2. Entry flow patterns (v_e = entry velocity, V = free stream velocity).

vanes which are sometimes arranged to vary their angular setting over part of the r.p.m. range of the engines.

The hub-tip ratio of the compressor entry is about 1/2, so that the rotational speed of the first stage blade roots is about 1/2 that of the blade tips. The mean velocity of the air entering the compressor is very roughly about 1/3 of the blade tip speed, so that a local change of 10 per cent. in the air velocity will result in a change of the incidence of the air on the blades of about $1\frac{1}{2}°$ at the tip and 3° at the root. Clearly it is quite possible for comparatively small changes in velocity distribution to affect the performance of these compressor blades, particularly when they are already at some critical value of incidence.

This point can be examined more conveniently by means of the conventional non-dimensional plot of compressor characteristics (Fig. 4). (There is an interesting recent American article in the December 1953 issue of the *Journal of the Aeronautical Sciences*, which uses this same approach). Compressor characteristics are curves of compression ratio against air flow at various values of rotor tip Mach number (N represents tip speed, and $\sqrt{T}$ the velocity of sound in the inlet air). As the flow through the compressor is reduced the compression ratio rises to a peak and then falls again. Clearly it is impossible to run stably (*i.e.* without surging) at flows below the value at the peak, so that there is a limit to the practical use of the compressor, which is called its "surge line." When the compressor is used in an engine, the flow areas at the turbine and final nozzle are adjusted so that the engine working line is just clear of the surge line.

2.1. ENGINE ACCELERATION REQUIREMENTS

Here there are two conflicting requirements. Firstly it so happens that the peaks of the compressor efficiency curves usually coincide roughly with the peaks of the compression ratio curves, so that it is very desirable to work as near to the surge line as possible. But secondly, to be able to handle the engine reasonably, for example to accelerate it quickly, the working line must be kept away from the surge line.

For if, when the engine is running steadily at a point on one of these characteristics, more fuel is introduced to accelerate the engine, the first result is to raise the temperature of the gases leaving the combustion chamber; these have to pass through passages which are usually "choked," *i.e.* are working at a fixed value of $W\sqrt{T}/P$ (measured in terms of compressor exit temperature and pressure), so that since the temperature has increased the air flow must drop, and the engine is momentarily working nearer the surge line. Thus sufficient margin must be left between the working line and the surge line to allow the engine to be accelerated. The final position of the working line is therefore a compromise between high efficiency (*i.e.* high thrust, low specific consumption) and ease of handling. This will always be the case, however much the surge line is raised by improvements in blade shape, etc., since it will always be desirable to raise the working line also, for the sake of the improved efficiency then obtainable.

Effect of non-uniform velocity distribution

At the lower end of the engine speed range compressor surge is due to stalling of the front stages of the compressor. It is therefore clear that areas of low velocity at entry to the compressor, resulting in increased incidence locally on the blades, will cause the stall to occur earlier in these regions, and hence will drop the surge line and reduce the acceleration margin.

An example of such a low velocity area is shown in Fig. 5, in which the velocity distribution at the entry to the engine is plotted for a short pitot intake under ground running conditions. Since the intake is circular the flow pattern is axi-symmetric, and hence is completely defined by one radial traverse. It can be seen that with the first rather sharp lip shape a separation occurred behind the lip, resulting in a large area of zero velocity round the outer periphery of the engine entry.

Quite a lot of thought has been given to a simple means of expressing the goodness or badness of such a velocity distribution picture. Since it is the regions of low velocity which are significant, some criterion which

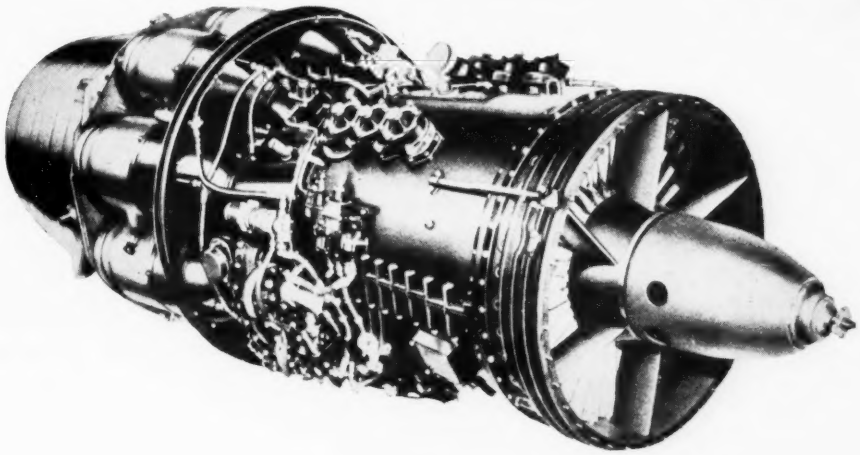

FIGURE 3. A typical axial compressor engine.

integrates these is wanted. One such criterion is the integral

$$\frac{1}{A}\int\left(1-\frac{v}{\bar{v}}\right)dA$$

taken over the area over which v is less than $\bar{v}$; another is a root mean square summation of the measured velocities,

$$\frac{1}{A}\sqrt{\left[\Sigma\left(\frac{v}{\bar{v}}\right)^2 dA\right]}$$

over the whole area. Much the simplest is the ratio of the maximum velocity at any point to the mean velocity over the whole area, $v_{max}/\bar{v}$. At first sight it might seem more logical to use the minimum velocity rather than the maximum, but as the velocity always falls to zero in the boundary layer the value of $v_{min}/\bar{v}$ would always be zero. And since the maximum velocity only rises above the mean due to the presence of areas of low velocity, the amount by which the ratio $v_{max}/\bar{v}$ exceeds 1 is quite a fair measure of the amount of low velocity present.

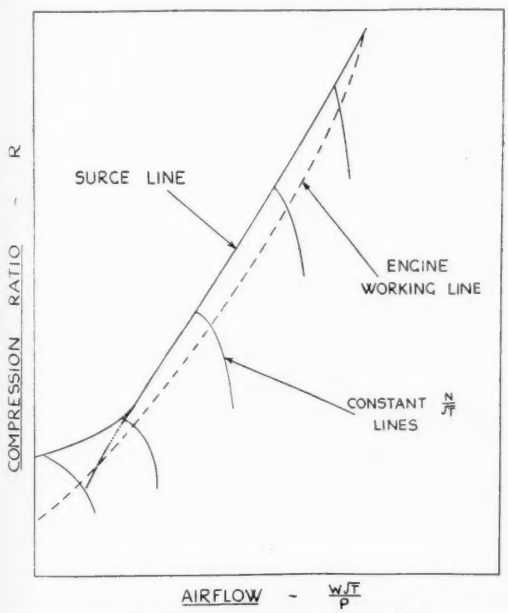

FIGURE 4. Axial compressor characteristics.

But having found a suitable measure of the velocity distribution, is it possible to determine its effect on the engine quantitatively? The answer is—in some cases, yes. It is a characteristic of axial compressors that their surge lines usually have a pronounced kink in them, so that the acceleration margin is usually at a minimum at a particular part of the engine speed range. Some measure of the margin available at this point is wanted, and on engines on which the inlet guide vane angle is normally varied over the speed range we can sometimes measure this margin directly.

For if on slowly decelerating the engine the inlet guide vane angle is deliberately held fixed at its high r.p.m. value, the engine will eventually surge when the working line intersects the new artificial surge line shown dotted on Fig. 4. With a bad velocity distribution this surge point will be reached earlier; the surge speed measured with a particular intake will be higher than that with a bell-mouth entry, and the difference gives a measure of the effect of the non-uniform velocity distribution of that intake on the acceleration margin of the engine.

Figure 6 shows the sort of relationship obtained on a particular engine. On this engine the artificially measured surge speed occurred at about 1,000 r.p.m. below the speed at which the inlet guide vane angle normally starts to alter. If therefore with a particularly bad distribution this surge speed was raised by 1,000 r.p.m. or more, it would be brought into the normal running range of the engine, and the engine would obviously be impossible to handle. In practice it was found that a difference in surge speed of about two-thirds of this figure could be tolerated, indicating that the velocity distribution had to be no worse than that represented by a $v_{max}/\bar{v}$ of about 1·3—unless of course changes were made to the engine, reducing its efficiency and increasing its specific consumption, to shift its working line farther from its surge line.

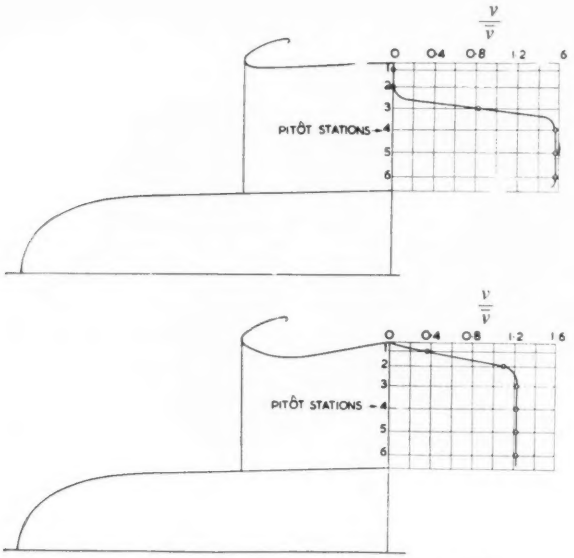

FIGURE 5. Ground running with short pitot intake.

2.2. HIGH $N/\sqrt{T}$ SURGE

So far the effects of non-uniform velocity distribution have been considered at low engine r.p.m. when the front stages of the compressor are stalled. Similar effects are observed at very high r.p.m. when it is the rear stages of the compressor that are stalled instead, and in this case it is difficult to see how a non-uniform distribution at entry can have any effect on the rear stages. The only plausible theory is to the effect that under these conditions there are choked passages at the front of the compressor, and that variations of velocity will cause "wakes" from these to spread rearwards and to affect the rear stages. In this case it is presumably local high velocities which do the damage indirectly, so that the same criterion as before, $v_{max}/\bar{v}$, should serve to define the badness of the distribution.

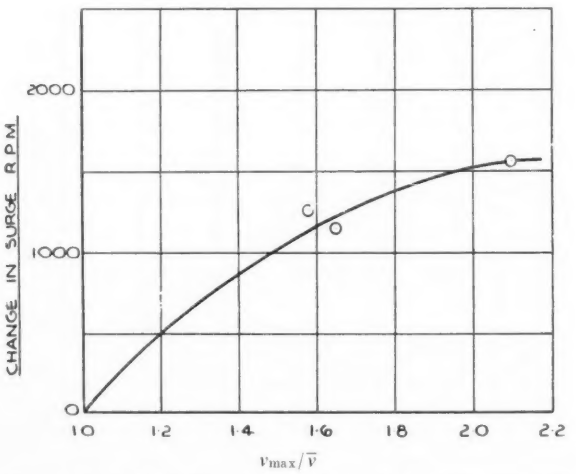

FIGURE 6. Relation between surge r.p.m. and velocity variation at compressor entry: acceleration conditions.

Under these conditions the effect on the engine can be measured directly without resorting to any artificial adjustments—provided that the engine can be run at low inlet temperatures, which means (in this country where there are no large high altitude test plants) in the air at high altitudes. For it is a characteristic of every jet engine—not only those with axial compressors—that if they are run up to a high enough r.p.m. the working line will eventually meet the surge line. It is of course the rotor tip Mach number which matters, not the tip speed, so that it is actually a high value of $N/\sqrt{T}$ at which the surge eventually occurs. If an engine is surge-free at its normal maximum r.p.m. under the extreme temperature conditions of, say $-80°$C., at a height where the minimum true air speed of an aircraft might be 300 m.p.h. giving 9° ram temperature rise, then at 15°C. this is equivalent to being surge-free at an r.p.m. nearly 20 per cent. greater than its normal maximum.

Once again every engine is designed to operate as near to this surge limit as possible, as before, with the object of running at as high an efficiency as possible. And again the effect of a non-uniform distribution is to lower the surge line and hence reduce the margin of surge-free operation, this time under steady running conditions at maximum r.p.m. at extreme temperatures.

Figure 7 shows the order of the effect. In this case a more direct assessment of the value of a good distribution can be obtained, since it turns out that the cost of an increase in the surge margin of an engine of 10 units of $N/\sqrt{T}$ (obtained by means of a shift in the working line) might be an increase of about 2 per cent. in specific consumption. Hence to maintain the same margin of surge-free operation with a velocity distribution defined by a $v_{max}/\bar{v}$ of only 1·16 will cost 2 per cent. in specific consumption. This equivalence will vary from engine to engine, but the importance of a good velocity distribution to the ultimate performance of an engine is clear.

2.3. BLADE VIBRATION

Quite apart from the effects of non-uniform velocity distributions on the performance of the engine compressor, there is also the possible effect on the fatigue life of the compressor blades due to vibration excited

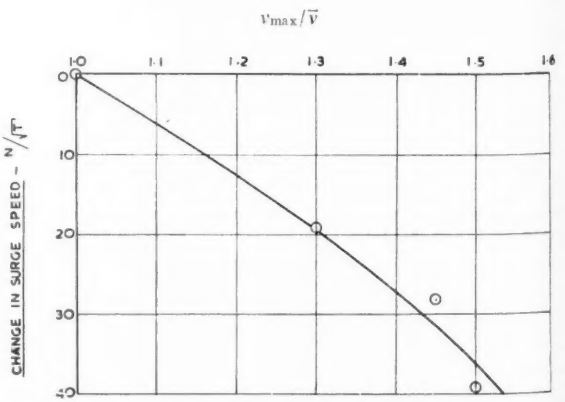

FIGURE 7. Relation between surge r.p.m. and velocity variation at compressor entry: high $N/\sqrt{T}$ surge.

aerodynamically as the blades pass through areas of varying velocity. A full theoretical treatment of this subject will be found in Pearson's paper "The Aerodynamics of Compressor Blade Vibration" presented to the Fourth Anglo-American Aeronautical Conference in London in September 1953; the following remarks will be based on this paper.

By an analysis of the varying force exerted on a blade due to a sinusoidal variation of incidence, and of the inherent damping of the air due to the blade velocity, Pearson derives an expression for the stress induced in a blade vibrating at its resonant frequency as a result of its passage through areas of varying velocity. This stress is found to be proportional to Δv, the (sinusoidal) component of velocity variation across the plane of the compressor blades at the appropriate resonant frequency; for aluminium alloy blades this works out to the very simple expression

$$\text{root stress} = 1066\Delta v \text{ lb./in.}^2$$

when Δv is in ft./sec.

The significance of this result can be seen by examining a typical velocity distribution. The top graph of Fig. 8 shows the variation of velocity right round the compressor entry at a radius corresponding to half the blade height, measured behind the six struts supporting the front bearing, with a particular intake. This is a divided intake, and the large wake behind the division between the ducts can be seen swamping any wake from the struts at these points, and also the small wakes behind the other four struts. A Fourier analysis has been made of this velocity distribution and the predominating components are the 2nd, 4th, 6th and 12th engine orders, as shown. These four components have been recombined in the bottom graph and although there obviously are higher orders which should be taken into account, the original velocity distribution is quite closely reproduced. Assuming that this distribution exists over the whole blade height, what does it do to the engine? The 12th order component is small, the 6th order component is quite large but need not be considered, since no designer who puts six struts in front of his engine is going to allow a 6th order resonance to appear in the running range. The 2nd and 4th order components, however, are quite large, and might give trouble if there were a blade resonance at these frequencies. They amount to some 12 to 14 per cent. of the mean velocity, which might be of the order of 300 ft./sec.; Δv is therefore of the order of 40 ft./sec. and the fluctuating root stress in an aluminium alloy blade would be over 40,000 lb./in.^{2} if there were a resonance at the appropriate frequency. Pearson gives a figure of about 25,000 lb./in.^{2} as a reasonable limiting allowable stress, so that it is obviously possible for a velocity distribution of this sort to break blades quite quickly.

Fortunately the velocity variation is not usually the same over the whole blade height, so that the overall excitation is usually much less than the extreme case measured at any one radius—and there is usually some mechanical damping of the blade which is ignored in these calculations—and in any case it should be possible to design the important resonances out of the running range of the engine, so that it is usually possible to avoid these troubles. Nevertheless it is clear that a non-uniform velocity distribution can be hard on the engine, which might well have to suffer some weight or performance penalty in order to make sure of avoiding trouble from blade vibration excited aerodynamically.

3. Intake Design for Good Velocity Distribution

So far some reasons have been given for the importance of having a reasonably good distribution of velocity at the engine entry, and some sort of quantitative estimate has been made of what is meant by "reasonably good." It appears that from the point of view of handling the engine satisfactorily a $v_{max}/\bar{v}$ of 1·3 might be a reasonable figure, but that for ultimate

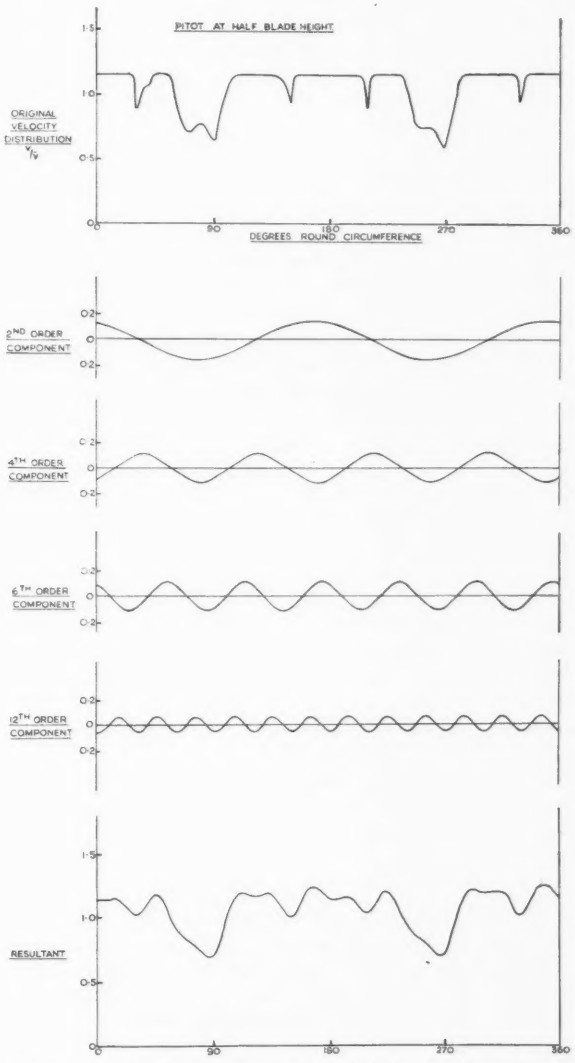

FIGURE 8. Aerodynamic excitation of blade vibration: Fourier analysis of typical velocity distribution.

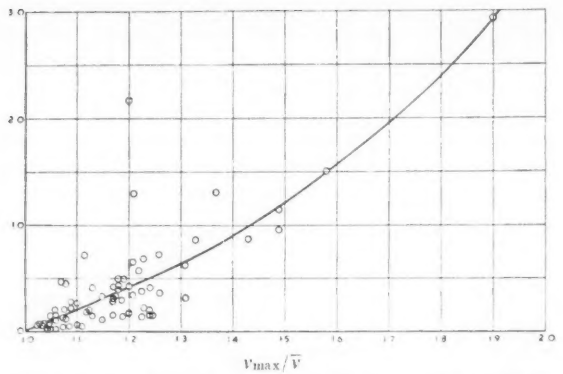

FIGURE 9. Relation between pressure losses and velocity distribution: measured on 11 different intakes, at values of V/v from 0 to 3, at incidences from 0 to $12\frac{1}{2}°$.

performance something much better than this is necessary, perhaps less than 1·1.

The various conditions under which an air intake has to operate in an aircraft will now be examined more carefully, and the design principles which should be followed in order to obtain a good velocity distribution at the engine will be discussed briefly—only briefly because the principles are in fact precisely the same as those required to obtain low pressure losses. Obviously there are exceptions to this rule; cases will arise where low losses are accompanied by bad distribution, and it would be easy to obtain a good distribution at the expense of high losses, by means of a gauze for example. Nevertheless it is generally true that an intake designed to give low losses under all conditions of operation will also have a good distribution under all these conditions.

This point is illustrated in Fig. 9, in which the losses in a number of different intakes are compared with the corresponding velocity distributions. The loss coefficient λ (total head loss/mean dynamic head at compressor) has been plotted against the corresponding value of $v_{max}/\bar{v}$ for 11 different intakes over a range of incidences and velocity ratios. In spite of the scatter of the results there is a fair correlation between the magnitude of the losses and the badness of the velocity distribution. The two high loss points at $v_{max}/\bar{v}=1·2$ are particularly interesting in that they would not be expected to lie on the mean curve; they were measured on intakes on which a number of vanes were inserted for the sole purpose of improving the velocity distribution at the expense of high losses. In general, therefore, the principles outlined by Seddon*, primarily to obtain high efficiency, hold good just as much for good distribution.

Ground running

From the point of view of the engine designer the best form of intake for ground running would obviously be a large bell mouth. However, since an insistence on this would retard the sales of his product some compromise must be arrived at between this requirement and that of the aircraft manufacturer (who would of

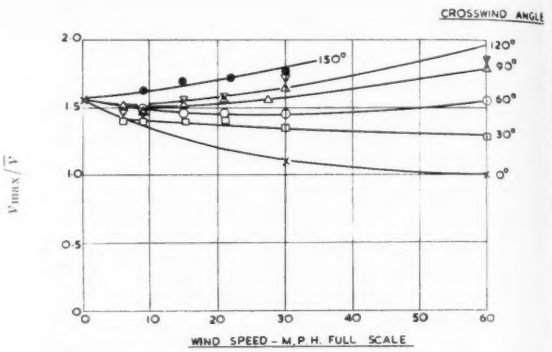

FIGURE 11. Crosswind effects: variation of $v_{max}/\bar{v}$ with wind speed and crosswind angle.

course prefer the intake to take up no space at all). Two examples of the sort of compromise which can be found are illustrated by:—

1. A very short pitot intake (Fig. 5). In its original form this had a severe separation behind the intake lip, resulting in a large area of zero velocity at the compressor blade tips; $v_{max}/\bar{v}$ was nearly 1·6. The modification shown in the lower diagram consisted of a fairing added internally to give a contraction in area from the "high light"† to the throat of 20 per cent.; neither the lip radius nor the outside shape were touched; in spite of the increased diffusion along the duct the separation has been practically suppressed and $v_{max}/\bar{v}$ reduced to just over 1·2.
2. An intake with about 25° tilt to the entry, but with the duct arranged roughly along the line of flight (Fig. 10). On the ground, air approaches in a general direction normal to the entry, so that a separation occurred on the lower lip; $v_{max}/\bar{v}$ was 1·39. The internal fairing—again purely internal—increased the contraction ratio slightly, but its main effect was to make the duct direction start normal to the entry; $v_{max}/\bar{v}$ was reduced to 1·14.

Two simple rules for the design of intakes satisfactory for ground running, therefore, are:

(*i*) A contraction in area from "high light" to throat of at least 20 per cent.,

(*ii*) Duct direction at the entry to be normal to the entry.

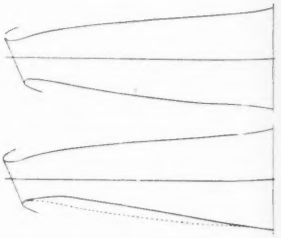

FIGURE 10. Ground running with tilted entry.

*Air Intakes for Aircraft Gas Turbines, J. Seddon, *Journal of the Royal Aeronautical Society*. October 1952.

†Defined by the plane(s) normal to the line of flight which just touches the lips of the intake.

Cross Wind Effects

There is another point which must be considered under ground running conditions—the effect of cross winds, as aircraft cannot always have their engines run up facing directly into wind. Fig. 11 shows the effect of cross winds on the velocity distribution obtained with a short pitot intake. There are some interesting points to be noted: —

(*i*) the effect of forward speed at zero cross wind angle as in a normal take-off. The bad distribution has practically disappeared at 30 m.p.h. and has completely gone at 60 m.p.h. so that it would have no effect by the end of the take-off run.

(*ii*) even with a cross wind, the flow first improves with wind speed before deteriorating again—the worst case tested was with the wind almost from the rear, but presumably this is a case which could be avoided; the most extreme case likely to be encountered in practice is perhaps a wind at 90°, and for this case the distribution is no worse than with zero wind up to a wind speed of about 30 m.p.h.

There is not yet a great deal of data on this effect, but it is probable that it is only a serious problem on very short intakes; with long ducts local lip separations probably clean up before reaching the engine.

In Flight

In flight there is a very wide range of operating conditions over which an air intake has to function satisfactorily. Fig. 12 shows this range in terms of aircraft

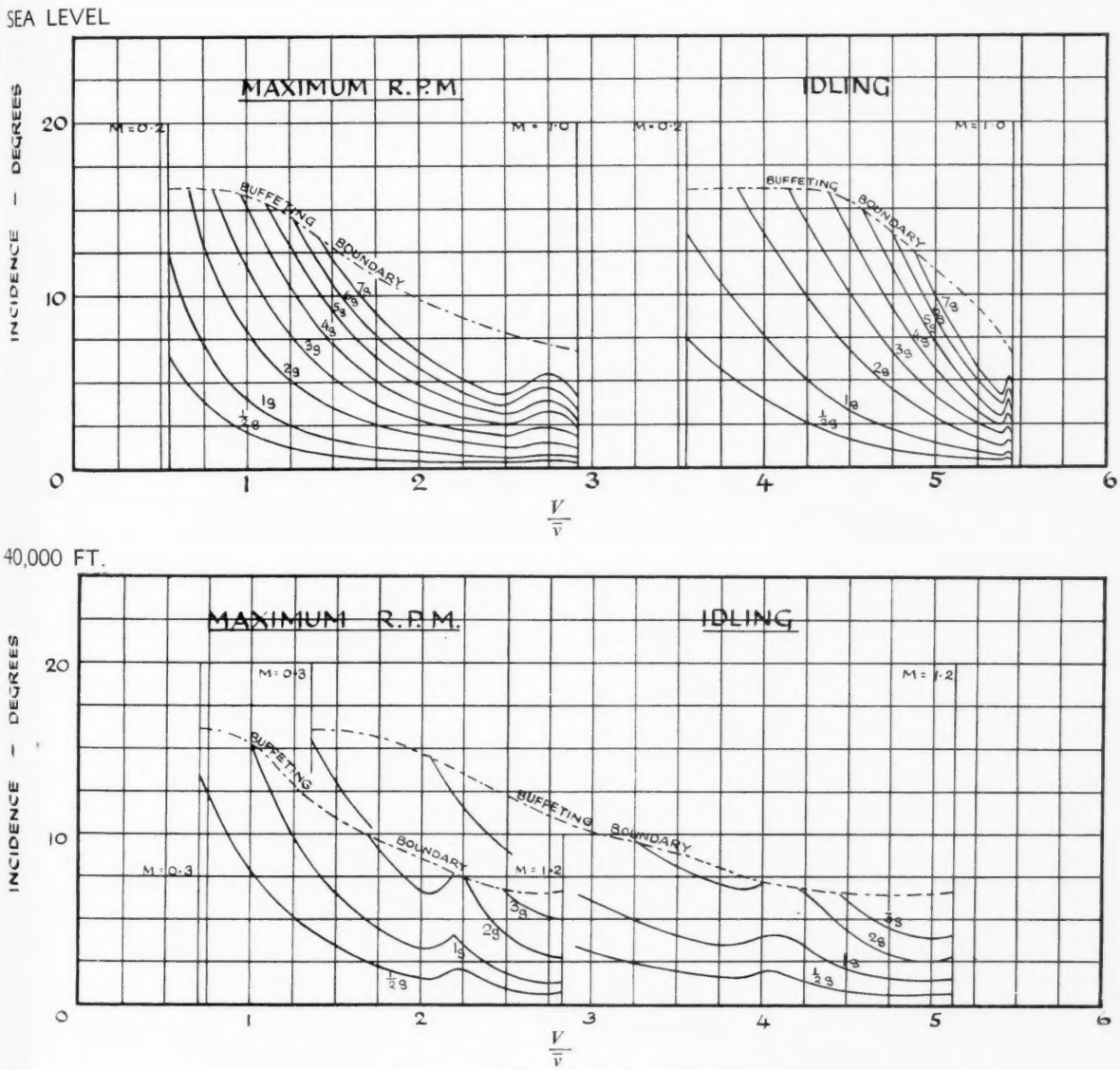

FIGURE 12. Operating range of air intakes.

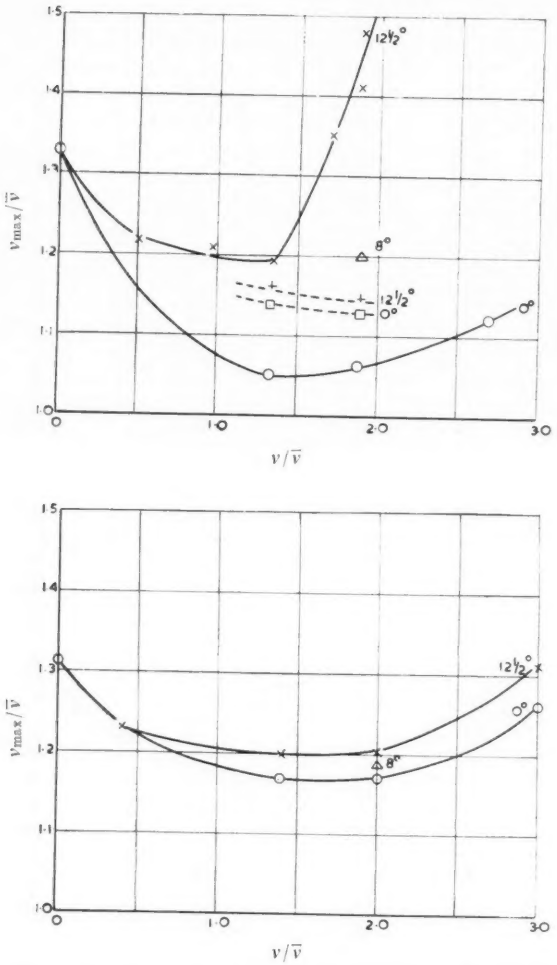

FIGURE 13. Variation of velocity distribution in flight for two typical intakes at various angles of incidence.

incidence and intake velocity ratio for the extremes of engine r.p.m. at two different altitudes. The figure is drawn for a typical axial jet engine in a typical modern transonic aircraft—speeds from $M=0{\cdot}2$ up to $M=1$ are included at sea level and from $M=0{\cdot}3$ up to $M=1{\cdot}2$ at 40,000 ft.—and it will therefore cover the cases of all aircraft flying at these or lower speeds. Of course both (so-called) negative g and positive g operation must be considered—the engine must not surge just because the aircraft has been put into a dive or into a high speed turn—so that lines have to be drawn to cover the range from $\frac{1}{2}g$ to $7g$ at sea level (using the notation in which $1g$ represents level flight) and from $\frac{1}{2}g$ to $3g$, probably the maximum attainable, at high altitude. The maximum r.p.m. and idling regimes are quite separate at sea level, but overlap somewhat at 40,000 ft. From this graph the operating condition of the intake can be determined over the whole range of flight conditions from the end of the take-off run, climb, level flight, turns, descent, dive, back to landing (not forgetting a baulked landing). The velocity ratio used in the graph is aircraft velocity/mean velocity at entry to engine, so that the curves are independent of intake inlet area. (This inlet area is usually of the order of 3/4 of the engine entry area, and the corresponding velocity ratios based on inlet area are therefore also about 3/4 of those on the graph.)

Where in all this operating range is the velocity distribution at the engine of importance? Considering the three engine troubles already described in turn,

(1) engine acceleration—low and intermediate r.p.m. under all aircraft conditions. The sea level curves show that these can occur at all possible angles of incidence at values of V/v of about 2 to 4. The high altitude curves show that the V/v range must be extended down to about 1.

Summarising, the important conditions are at all incidence from 0 to 16° and all values of V/v from 1 to 4.

(2) high $N/\sqrt{T}$ surge—this requires maximum r.p.m., high altitude and primarily low speed (for low temperatures). Obviously this is a much narrower range which can be summarised as being all incidences from 0 to 16° and all values of V/v from 0·7 to 1·7.

(3) possible blade vibration—this is usually only dangerous if it occurs at intermediate to high r.p.m., at any sustained conditions of flight (*i.e.* only at $1g$). Again this is quite a narrow band of conditions varying from incidence 0, $V/v=2$ to 3·5 up to incidence 16°, $V/v=0{\cdot}7$ to 2.

Clearly the second and third cases occur over only quite restricted conditions of flight. For example at high incidence, and really high V/v, which can only occur in a high speed turn with the engine throttled back at low altitude, high $N/\sqrt{T}$ troubles requiring maximum r.p.m. will not occur, nor blade vibration troubles requiring reasonably sustained conditions.

The behaviour of some typical intakes has been examined under these important conditions. Fig. 13 shows the variation of velocity distribution (still measured as $v_{max}/\bar{v}$) with V/v and with incidence, for two particular air intakes.

The full lines show the performance of intake *A* in its original form; neglecting the ground running case at this stage, it can be seen that at zero incidence the distribution is very good but that it gets very bad at high incidence. From these curves it is clear that low r.p.m. engine handling difficulties ($v_{max}/\bar{v}>1{\cdot}3$) might be expected to occur only at extreme angles of incidence, but that high $N/\sqrt{T}$ performance ($v_{max}/\bar{v}>1{\cdot}1$) might be affected at moderate to high incidences. (The parameter $v_{max}/\bar{v}$ is not of course sufficient to give any information about blade breaking conditions, for which this graph is of no value.) The reason for the deterioration with incidence is that in its original form this intake had only 22° tilt at the wing leading edge, at which large angles of upwash would be expected. A small extension of the upper lip, increasing the tilt to 34°, in combination with a fairing inside the lower lip similar to the one shown in Fig. 10, had the effect shown by the dotted

lines. Clearly the low r.p.m. handling difficulties should be completely eliminated; as far as the high $N/\sqrt{T}$ performance is concerned, the incidence effect has disappeared, and the performance at all incidences is now a little worse than it was before at zero incidence. Further work on this intake would be desirable if the penalty in ultimate performance were too great.

Intake *B* is rather different. Low r.p.m. handling difficulties would not be expected to appear at all, but high $N/\sqrt{T}$ performance will be affected at all flight conditions. The reason for the basic difference between intake *A* and intake *B* lies in the variation of area along the ducts; both intakes have a bend in them just before reaching the engine, but intake *A* has a considerable contraction in area round this bend, whereas intake *B* diffuses all the way round the bend, with the result that a boundary layer separation occurs.

The lessons to be learnt from these results then are:

(*i*) that the tilt of the entry should be matched to all the flow directions which it is likely to meet,

(*ii*) that any changes in duct direction should be accompanied by a contraction in area sufficient to suppress any adverse pressure gradient, or at least to keep it small enough to prevent boundary layer separation from occurring.

4. Matching of Intake Velocity Distribution to Engine Requirements

An attempt has been made in this paper to show why, to get the best out of an engine intake combination,

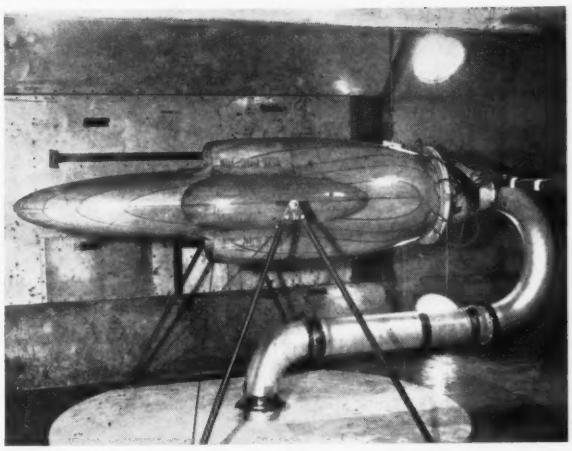

FIGURE 14. ¼-scale model set up in wind tunnel for intake tests.

it is necessary to pay attention to the velocity distribution in an intake; to sugest how good the distribution ought to be; to explain the ground running and flight conditions under which trouble might be expected from the engine if the distribution is not good enough; and to suggest a few principles which can be adopted to make it so.

But when a new prototype is only on paper, although these principles can be applied to the design of the air intake, it is still not possible to predict exactly what the distribution will be. And when a new engine is involved it is not possible to stipulate exactly how good

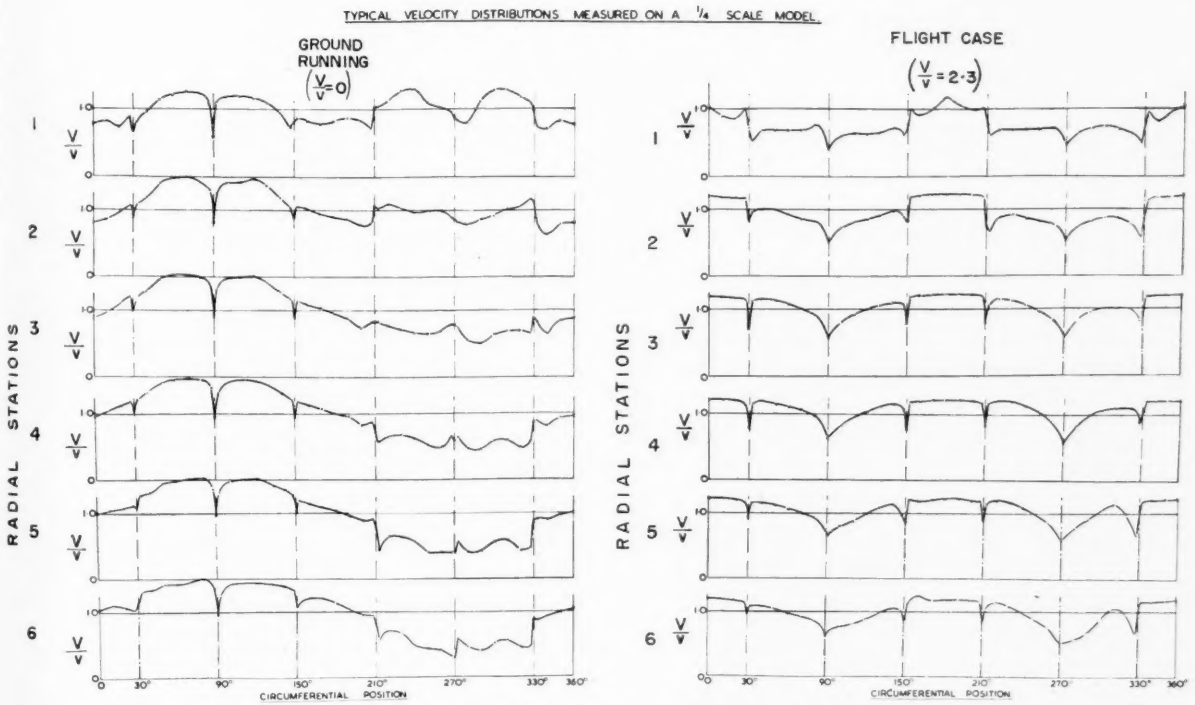

FIGURE 15. Typical velocity distribution measured on a ¼-scale model.

the distribution ought to be, since of course there is bound to be variation between engines in the way they react to a bad distribution—some will be more sensitive than others. Special steps should therefore be taken to deal with the problem of matching intake velocity distribution to the engine on future aircraft, and the following is an outline of the procedure which might be followed.

Model Tests

First a model of the air intake should be tested in a wind tunnel, under all the conditions of incidence and V/v likely to be encountered.

Figure 14 shows such a $\frac{1}{4}$-scale model in the Rolls-Royce 7 ft. × 5 ft. low-speed tunnel at Hucknall; all parts of the aircraft likely to affect the flow into the intake should be represented. Such a model has a very large blockage effect, but since forces are not being measured this is not a serious difficulty, and very reasonable correlation has been found between velocity distribution measurements full scale and $\frac{1}{4}$ scale; still smaller scales would certainly be satisfactory but the difficulties of getting in the necessary instrumentation become progressively greater.

A radial rake of 6 pitots is normally used, arranged so that each is at the centre radius of 6 annuli of equal area (to simplify the subsequent analysis), as illustrated in Fig. 5: the rake can be rotated through 360° from outside the tunnel so that it can traverse the whole of the engine entry and in some cases, depending on the uniformity of the distribution being measured, readings are taken every $2\frac{1}{2}°$.

Figure 15 shows two typical sets of such traverses, at ground running and at a typical flight condition at zero incidence. It can be seen that these distributions are not very good, and are quite different from each other.

Engine Tests

This intake is to be used with a new engine, so the next step is to determine whether the engine will tolerate these velocity distributions without undue penalty in handling, ultimate performance, or blade vibration. As far as the ground running case is concerned this is fairly easy. A full-scale model intake can be made and run on the engine on the test-bed; the handling can be checked directly, and the blade vibration can be measured by means of strain gauges fixed to the blades (this of course is preferable to just running the engine to see if it breaks!).

The flight case is more difficult, since it needs an intermediate step, the making up of a special piece of ducting in which the particular flight velocity distribution needing investigation can be simulated by means of blockages, gauzes, and so on, which can then be run on the engine. The difficulty lies in the fact that the process can be rather tedious since a certain amount of trial and error is usually necessary to get really good agreement between model and test intake. Once again the engine can be checked for satisfactory handling and for blade vibration on the test-bed with this test intake. To examine the effect on high $N/\sqrt{T}$ surge characteristics, however, the engine must be taken up to high altitude, to obtain low air temperatures, in a flying test-bed aircraft, again with this simulated velocity distribution, and the surge measurements compared with those obtained with a perfect intake.

The story is then complete, and if the results are not good enough modifications must be made to the model, and the process repeated. Naturally, it is not necessary to go through the whole sequence of testing on the engine every time. After the first few tests of this kind it will be possible to lay down the standards of velocity distribution required, and it will then only be necessary to work directly on the model.

Flight Tests

The final judgment on the success or otherwise of the matching of air intake to engine must come from flight tests on the actual aircraft. And since the satisfactory functioning of the engine is surely equally as important as, say, the satisfactory functioning of the controls, such tests should be carried out quite early on in the prototype flight programme, so that any unexpected snags in an intake can be put right before it is too late.

5. Conclusion

In order to simplify the picture a little, a number of factors have been omitted which affect the matching of an intake velocity distribution to an engine; while this may be justified in this introduction to the subject, it is clear that much further work remains to be done.

ACKNOWLEDGMENT

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TECHNICAL NOTES

Contributions to this Section of the JOURNAL *will be eligible for Journal Premium Awards and will normally be published within two months of being received.*

Stability Criteria for the Octic Equation

by

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THE STABILITY CRITERIA for systems whose characteristic equations are of the eighth degree are expressed in a convenient form and a detailed scheme for the computation of the complete set of test functions in sequence is given. A special method for the direct calculation of the critical test function T_7 is also given; the vanishing of this determines the critical flutter speeds of quaternary systems.

1. INTRODUCTION

In a Note[1] already published stability criteria for "linear" systems with constant coefficients were discussed in a general way and a detailed treatment of the criteria for the sextic equation included a convenient scheme for the computation of the complete set of test functions in sequence. In the present Note a similar scheme is given for the octic equation, but it is inevitably much more complicated than the one for the sextic equation. The critical flutter speeds of a system with four degrees of freedom are determined by the vanishing of the penultimate test function T_7 of an octic equation. A convenient method for the direct calculation of T_7 and of the flutter frequency in the critical state is included.

2. THE CRITERIA FOR STABILITY

The octic equation under discussion will be written

$$f(\lambda)\equiv p_8\lambda^8+p_7\lambda^7+p_6\lambda^6+p_5\lambda^5+p_4\lambda^4+p_3\lambda^3+ +p_2\lambda^2+p_1\lambda+p_0=0 \quad . \quad . \quad (2.1)$$

and it will be supposed that p_8 is positive. Then the complete set of necessary and sufficient conditions for stability is

$$T_1=p_7>0 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2.2)$$

$$T_2=\begin{vmatrix} p_7 & p_8 \\ p_5 & p_6 \end{vmatrix}>0 \quad . \quad . \quad . \quad . \quad . \quad . \quad (2.3)$$

$$T_3=\begin{vmatrix} p_7 & p_8 & 0 \\ p_5 & p_6 & p_7 \\ p_3 & p_4 & p_5 \end{vmatrix}>0 \quad . \quad . \quad . \quad . \quad . \quad (2.4)$$

$$T_4=\begin{vmatrix} p_7 & p_8 & 0 & 0 \\ p_5 & p_6 & p_7 & p_8 \\ p_3 & p_4 & p_5 & p_6 \\ p_1 & p_2 & p_3 & p_4 \end{vmatrix}>0 \quad . \quad . \quad . \quad (2.5)$$

$$T_5=\begin{vmatrix} p_7 & p_8 & 0 & 0 & 0 \\ p_5 & p_6 & p_7 & p_8 & 0 \\ p_3 & p_4 & p_5 & p_6 & p_7 \\ p_1 & p_2 & p_3 & p_4 & p_5 \\ 0 & p_0 & p_1 & p_2 & p_3 \end{vmatrix}>0 \quad . \quad . \quad (2.6)$$

$$T_6=\begin{vmatrix} p_7 & p_8 & 0 & 0 & 0 & 0 \\ p_5 & p_6 & p_7 & p_8 & 0 & 0 \\ p_3 & p_4 & p_5 & p_6 & p_7 & p_8 \\ p_1 & p_2 & p_3 & p_4 & p_5 & p_6 \\ 0 & p_0 & p_1 & p_2 & p_3 & p_4 \\ 0 & 0 & 0 & p_0 & p_1 & p_2 \end{vmatrix}>0 \quad (2.7)$$

$$T_7=\begin{vmatrix} p_7 & p_8 & 0 & 0 & 0 & 0 & 0 \\ p_5 & p_6 & p_7 & p_8 & 0 & 0 & 0 \\ p_3 & p_4 & p_5 & p_6 & p_7 & p_8 & 0 \\ p_1 & p_2 & p_3 & p_4 & p_5 & p_6 & p_7 \\ 0 & p_0 & p_1 & p_2 & p_3 & p_4 & p_5 \\ 0 & 0 & 0 & p_0 & p_1 & p_2 & p_3 \\ 0 & 0 & 0 & 0 & p_0 & p_1 & p_2 \end{vmatrix}>0 \quad (2.8)$$

$$p_0>0. \quad . \quad . \quad . \quad (2.9)$$

When the system is not stable the number of "unstable" roots (those with their real parts positive) is equal to the number of changes of sign in the sequence $p_8p_7R_2R_3R_4R_5R_6R_7p_0$, where

$$R_n=\frac{T_n}{T_{n-1}} \quad . \quad . \quad . \quad (2.10)$$

and only the signs of the functions R need be obtained from the relations (2.10).

The direct computation of the higher members of the series of test determinants is laborious, but the same results can be obtained with less labour by use of the following formulae which can be obtained by partial expansion of the determinants:—

$$T_2=p_7p_6-p_8p_5 \quad . \quad . \quad . \quad . \quad . \quad . \quad (2.11)$$

$$\left.\begin{aligned} D_1&=p_7p_4-p_8p_3\\ D_2&=p_7p_2-p_8p_1\\ D_3&=p_7p_0-p_6p_1\\ D_4&=p_5p_4-p_6p_3\\ D_5&=p_3p_2-p_4p_1\\ D_6&=p_3p_0-p_2p_1\\ D_7&=p_3p_5-p_1p_7\\ E&=p_0p_7^2-p_1p_5p_8 \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad (2.12)$$

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$$T_3 = p_5 T_2 - p_7 D_1 \quad . \quad . \quad . \quad . \quad . \quad . \quad (2.13)$$

$$T_4 = p_4 T_3 + (D_2 - p_1 p_6) T_2 + p_5 p_8 D_1 \quad . \quad . \quad (2.14)$$

$$T_5 = p_3 T_4 - p_2 p_5 T_3 + (p_7 D_5 - p_5 D_3) T_2 + D_1 E - p_7 D_2^2 \quad . \quad . \quad (2.15)$$

$$T_6 = p_2 T_5 - p_1 p_4 T_4 + (p_0 D_4 + p_1 p_2 p_6) T_3 + \\ + \{p_0 (p_1 T_2 - p_3 D_1 - p_0 p_7^2) + p_1 (p_6 D_3 - p_8 D_5)\} T_2 + \\ + (p_0 p_7 D_2 - p_1 p_8 D_3) D_1 + p_1 p_8 D_2^2 \quad . \quad . \quad (2.16)$$

$$T_7 = p_1 T_6 - p_0 p_3 T_5 + p_0 p_1 p_5 T_4 + \\ + p_0 (p_7 D_6 - p_0 p_5^2) T_3 + p_0 p_7 (p_0 D_7 - p_1 D_3) T_2 - \\ - p_0 p_7 \{p_1^2 p_8 D_1 + p_7 (p_0 p_5 D_2 - p_0^2 p_7^2)\} . \quad . \quad (2.17)$$

3 SCHEME OF COMPUTATION

Calculate first the binary products:—

$$B_1 = p_8 p_5, \quad B_2 = p_8 p_3, \quad B_3 = p_8 p_1, \quad B_4 = p_7 p_6$$
$$B_5 = p_7 p_4, \quad B_6 = p_7 p_2, \quad B_7 = p_7 p_1, \quad B_8 = p_7 p_0$$
$$B_9 = p_6 p_3, \quad B_{10} = p_6 p_1, \quad B_{11} = p_5 p_4, \quad B_{12} = p_5 p_3$$
$$B_{13} = p_5 p_2, \quad B_{14} = p_5 p_0, \quad B_{15} = p_3 p_2, \quad B_{16} = p_3 p_0$$
$$B_{17} = p_1 p_4, \quad B_{18} = p_1 p_2, \quad B_{19} = p_1 p_0.$$

Now we obtain

$$T_2 = B_4 - B_1, \qquad D_4 = B_{11} - B_9$$
$$D_1 = B_5 - B_2, \qquad D_5 = B_{15} - B_{17}$$
$$D_2 = B_6 - B_3, \qquad D_6 = B_{16} - B_{18}$$
$$D_3 = B_8 - B_{10}, \qquad D_7 = B_{12} - B_7$$

$$E = p_7 B_8 - p_5 B_3, \quad D_2^2 \text{ and } B_8^2.$$

Then

$$T_3 = p_5 T_2 - p_7 D_1$$

$$T_4 = p_4 T_3 + (D_2 - B_9) T_2 + B_2 D_1$$

$$T_5 = p_3 T_4 - B_{13} T_3 + (p_7 D_5 - p_5 D_3) T_2 + D_1 E - p_7 D_2^2$$

$$T_6 = p_2 T_5 - B_{17} T_4 + (p_0 D_4 + p_2 B_{10}) T_3 + \\ + \{p_0 (p_1 T_2 - p_3 D_1 - p_7 B_8) + p_1 (p_6 D_3 - p_8 D_5)\} T_2 + \\ + (B_8 D_2 - B_3 D_3) D_1 + B_3 D_2^2$$

$$T_7 = p_1 T_6 - B_{16} T_5 + p_1 B_{14} T_4 + p_0 (p_7 D_6 - p_5 B_{14}) T_3 + \\ + B_8 (p_0 D_7 - p_1 D_3) T_2 - \\ - B_8 \{p_1 B_3 D_1 + p_7 (B_{14} D_2 - B_8^2)\}.$$

4. CALCULATION OF THE CRITICAL TEST FUNCTION T_7

It follows from the general theory that T_7 vanishes whenever (2.1) has equal and opposite roots, $\pm\beta$ say. When this is so we must have the equations

$$f_1(z) \equiv p_8 z^4 + p_6 z^3 + p_4 z^2 + p_2 z + p_0 = 0 \quad . \quad (4.1)$$

$$f_2(z) \equiv p_7 z^3 + p_5 z^2 + p_3 z + p_1 = 0 \quad . \quad . \quad (4.2)$$

satisfied simultaneously, with

$$z = \beta^2. \quad . \quad . \quad . \quad . \quad . \quad (4.3)$$

In the important case of a critical speed for flutter (or, in general, for an oscillatory critical state) $\beta = i\omega$ and

$$z = -\omega^2 \quad . \quad . \quad . \quad . \quad (4.4)$$

where ω is 2π times the frequency of the critical oscillation. The common root z must satisfy any equation obtained from (4.1) and (4.2) by partial elimination. One such equation is the quadratic*

$$Az^2 + Bz + C = 0 \quad . \quad . \quad . \quad (4.5)$$

where $A = p_7 (p_1 p_2 - p_0 p_3) - p_1^2 p_8 \quad . \quad . \quad . \quad (4.6)$

$$B = p_5 (p_1 p_2 - p_0 p_3) - p_1 (p_1 p_6 - p_0 p_7) \quad . \quad (4.7)$$

$$C = p_3 (p_1 p_2 - p_0 p_3) - p_1 (p_1 p_4 - p_0 p_5). \quad . \quad (4.8)$$

Let z_1 and z_2 be the roots of (4.5). Then T_7 must contain the product $f_2(z_1) f_2(z_2)$ as a factor and it can be shown by identification of coefficients that

$$T_7 = -\frac{A^3 f_2(z_1) f_2(z_2)}{p_1^4}. \quad . \quad (4.9)$$

It appears that

$$C = \begin{vmatrix} p_1 & p_0 & 0 \\ p_3 & p_2 & p_1 \\ p_5 & p_4 & p_3 \end{vmatrix} = T_3' \quad . \quad . \quad (4.10)$$

where T_3' is the third order test determinant for the equation

$$p_0 \lambda^8 + p_1 \lambda^7 + p_2 \lambda^6 + \ldots + p_8 = 0. \quad . \quad . \quad (4.11)$$

The roots of this equation are the reciprocals of the roots of (2.1) and they are necessarily "stable" when the roots of (2.1) are stable. Hence (with p_0 positive) T_3' must be positive when the system is stable.

When it is required to calculate T_7 we may use equation (4.9). However, a simpler procedure may be followed with advantage when the sole object is to locate a critical condition, as in flutter investigations. Thus, we calculate the roots z_1 and z_2 of the quadratic (4.5) and find whether either of them satisfies (4.2). The oscillation frequency in the critical condition is then obtained from (4.4), where z is now that root of (4.5) which satisfies (4.2). Since z is real and negative in the critical condition, it is at once evident that the system is *not* in a critical state if the roots of (4.5) are complex or both positive.

REFERENCE

1. DUNCAN, W. J. (1954). Stability Criteria, with Special Reference to the Sextic Equation. *Journal of the Royal Aeronautical Society*, June 1954, p. 431.

*This can be derived as follows: first obtain a cubic from (4.1) and (4.2) by eliminating the constant terms and dividing by z. Then eliminate the constant terms from this cubic and (4.2) and divide the result by z. Many other quadratic partial eliminants can be obtained by varying the process of elimination. One such is (with the notation of Section 2)

$$T_3 z^2 + (p_3 T_2 - p_7 D_2) z + (p_1 T_2 - p_0 p_7^2) = 0.$$

Flexural Vibration of Plates on Uniform Elastic Foundations

by

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THE FLEXURAL VIBRATION of uniform plates on uniform elastic foundations is of interest in connection with fatigue and sound intensity studies.

NOTATION

- A matrix of coefficients of $\nabla^2\nabla^2 w$ terms
- a width of plate
- c_n vibration coefficient for plates without springs
- D plate stiffness
- E Young's modulus
- I moment of inertia of ring or beam cross section
- I' unit matrix
- f constant relating grid spacing to plate width
- g gravitational acceleration
- k spring constant per length cubed for plate and per length squared for beam and ring
- L beam length
- n mode of vibration
- q lateral weight per length squared for plate and per unit length for beam and ring
- w plate deflection, positive downward
- r radius of ring
- $\beta_n = \dfrac{q\omega_n^2 a^4}{gD}$
- ω_n natural frequency in radians per second

SOLUTION

Consider any medium-thick unloaded flat plate and take co-ordinate axes x and y in the middle surface of the plate. The usual assumptions regarding medium-thick plates are made. The masses of the springs of the elastic foundation are neglected. If static loads are replaced with equivalent inertia loads when the plate is freely vibrating, the governing differential equation of the plate may be written as

$$D\nabla^2\nabla^2 w + kw - \frac{q\omega^2}{g} w = 0. \quad . \quad . \quad . \quad (1)$$

This equation may be written in finite difference form at a large number of points. The boundary conditions may be included in the difference patterns for various cases. The resulting simultaneous linear algebraic equations may be written matrically as

$$\left[\left(fA + \frac{ka^4}{D} I'\right) - \beta_n I'\right] w = 0. \quad . \quad (2)$$

This equation is in standard Eigenvalue form. Since the term ka^4/D is multiplied by a unit matrix it follows from the laws of matrix algebra that

$$\beta_n = c_n + \frac{ka^4}{D} \quad . \quad . \quad . \quad (3)$$

where c_n is a coefficient for the vibration of a plate without a foundation spring support. It should be apparent that when the sizes of the matrices in equation (2) become infinite the solution for β_n from equation (2) approaches the exact solution. The coefficient c_n is known exactly for some plates and very close approximate answers are available for other plates having various shapes and boundary conditions. It follows from equation (3) that

$$\omega_n^2 = \frac{gD}{qa^4}\left[c_n + \frac{ka^4}{D}\right] \quad . \quad . \quad (4)$$

It is seen that the square of a natural frequency increases linearly with the foundation modulus k. Equation (4) may be used to determine the natural frequencies of various plates on elastic foundations providing the coefficient c_n is known. For example, the fundamental frequency of a square simply-supported plate on an elastic foundation is

$$\omega_1^2 = \frac{gD}{qa^4}\left[4\pi^4 + \frac{ka^4}{D}\right],$$

and the fundamental frequency of a simply-supported right-angled isosceles triangular plate on an elastic foundation is

$$\omega_1^2 = \frac{gD}{qa^4}\left[25\pi^4 + \frac{ka^4}{D}\right]$$

where a is the length of a side of the triangle.

It is of interest to compare equation (4) with expressions for the natural frequencies of flexural vibration for beams and rings on elastic foundations. The natural frequencies for simply-supported beams are

$$\omega_n^2 = \frac{EIg}{qL^4}\left[n^4\pi^4 + \frac{kL^4}{EI}\right]$$

and the natural frequencies for circular rings* are

$$\omega_n^2 = \frac{EIg}{qr^4(1+n^2)}\left[n^2(1-n^2) + n^2\frac{kr^4}{EI}\right]$$

where k is a radial spring constant. It is seen that any particular natural frequency for a beam, ring, or plate on an elastic foundation is affected in the same general way by the foundation modulus k.

The technique discussed in this note for the approach to Eigenvalue problems has particular merit in certain cases. It is not necessary to determine Eigenvalues in the usual manner since the fundamental laws of matrix algebra reveal the physical behaviour of the structure and the relationship between various parameters.

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*WENKE, EDWARD, *Proceedings of the Society for Experimental Stress Analysis*, Vol. X, No. 2, 1953, p. 72.

The Natural Frequencies and Modes of Vibration of a Rotating Beam

by

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THIS NOTE presents in matrix form the equations of motion of a rotating and vibrating beam. The natural frequencies of the system are obtained by plotting an impedance–frequency diagram and noting the frequencies at which the impedance vanishes. Uncoupled bending vibrations are considered but the analysis can easily be extended to include coupled bending–torsion vibrations. The arrangement of the method for solution on a digital computor is quite straight-forward.

1. INTRODUCTION

The calculation of the normal modes and frequencies of a rotating beam is complicated by the existence of the centrifugal force field. Myklestad[1] solves the problem by using his extension of the Holzer method, which cannot readily be arranged for solution on a digital computor. Furthermore, it is necessary to maintain a very high degree of accuracy if any of the overtone modes are to be obtained. Horvay[2] makes an allowance for the stiffening effect of the centrifugal force field by using the non-rotating natural frequencies, in conjunction with certain "rotation coefficients." The results obtained from these two methods appear to agree reasonably well[3]. The method of this note is similar to that of Ref. 1 in that natural frequencies are located by plotting an impedance-frequency diagram, and using the fact that at a natural frequency the impedance of the system must vanish. The effects of the rotation are included by defining a set of "Equivalent Transverse Loads" (*see* Section 2). This is simply an artifice which enables one to relate beam bending moment distribution to the well known displacement—load influence coefficients.

NOTATION

m_j mass at station j

$M = \sum_{j=1}^{n} m_j$

n number of masses on the beam

x_j distance along the beam from the axis of rotation to station j

$M\bar{x} = \sum_{j=1}^{n} m_j x_j$

y_j amplitude of oscillation at station j

η_j, ζ_j components of y_j defined in Section 5

y_0 vertical displacement at station 0

ϕ_0 rotation about "flapping hinge" at station 0

$\bar{y}_i$ displacement at station i when $y_0 = \phi_0 = 0$

Ω angular velocity of rotation of beam

ω angular frequency of vibration of beam

M_{ij} bending moment in beam at station i due to forces acting on mass at station j

M_i total bending moment in beam at station i

F_j "equivalent transverse load" applied at station j

a_{ij} influence coefficient defining the vertical displacement at station i due to a unit vertical load at station j

$\bar{F}$ amplitude of externally applied shaking force at station 0

K_0 stiffness of rotational constraint at station 0 (flapping hinge spring stiffness)

$[A]$ $[B]$ $\{C\}$ $[D]$ matrices defined in Section 2

NOTE:—Station 0 will be described as the Root Station of the beam.

2. THE BENDING MOMENT DISTRIBUTION IN THE VIBRATING AND ROTATING BEAM

From Fig. 1, the inertia force in the y-direction on mass j is $\omega^2 m_j y_j$, the inertia force in the x-direction is $\Omega^2 m_j x_j$. Hence the bending moment at station i due to forces acting on mass j is

$$M_{ij} = \omega^2 m_j y_j (x_j - x_i) - \Omega^2 m_j x_j (y_j - y_i),$$

the total bending moment at station i being

$$M_i = \sum_{j=i+1}^{n} M_{ij}$$

or
$$M_i = \sum_{j=i+1}^{n} \{\omega^2 m_j y_j (x_j - x_i) - \Omega^2 m_j x_j (y_j - y_i)\} \qquad (1)$$

Rejecting as insignificant the shear and axial deformations in the beam, the deflected shape is uniquely determined by equation (1) in conjunction with the beam bending stiffness distribution. The latter is most conveniently expressed in terms of influence coefficients which relate displacements to transverse forces rather than bending moments. It is therefore necessary to obtain a set of "equivalent transverse loads" which will reproduce the beam bending moment distribution given by equation (1).

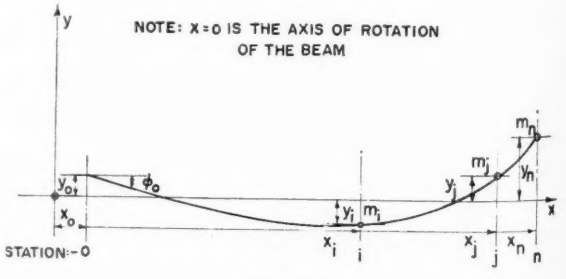

FIGURE 1.

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Applying to station j the equivalent transverse load F_j, the total bending moment at station i (in the stationary beam) will be

$$M_i = \sum_{j=i+1}^{n} F_j (x_j - x_i), \qquad . \quad . \quad (2)$$

and from equations (1) and (2)

$$\sum_{j=i+1}^{n} F_j (x_j - x_i) = \sum_{j=i+1}^{n} \{\omega^2 m_j y_j (x_j - x_i) - \Omega^2 m_j x_j (y_j - y_i)\}$$
$$. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Equation (3) can be expanded to give a set of linear simultaneous equations relating the equivalent transverse loads to the unknown displacements y_j. Such a set of equations can be best expressed as a single matrix equation

$$[A]\ \{F\} = [\omega^2 AD + \Omega^2 B]\ \{y\} - \Omega^2 y_0 \{C\} \quad . \quad (4)$$

where the matrices A, B, C and D are given as follows:–

$$[A] = \begin{bmatrix} (x_1 - x_0) & (x_2 - x_0) & (x_3 - x_0) & \ldots & (x_n - x_0) \\ 0 & (x_2 - x_1) & (x_3 - x_1) & \ldots & (x_n - x_1) \\ 0 & 0 & (x_3 - x_2) & \ldots & (x_n - x_2) \\ . & . & . & & . \\ . & . & . & & . \\ . & . & . & & . \\ . & . & . & & . \\ 0 & 0 & 0 & \ldots & (x_n - x_{n-1}) \end{bmatrix}$$

$$\{F\} = \{F_1\ F_2\ .\ .\ .\ .\ .\ F_n\}$$

$$\{y\} = \{y_1\ y_2\ .\ .\ .\ .\ .\ y_n\}$$

$$\{C\} = \{-M\bar{x}\ 0\ 0\ 0\ .\ .\ .\ 0\}$$

$$[D] = \begin{bmatrix} m_1 & 0 & 0 & \ldots & 0 \\ 0 & m_2 & 0 & \ldots & 0 \\ 0 & 0 & m_3 & \ldots & 0 \\ . & . & . & & . \\ . & . & . & & . \\ . & . & . & & . \\ . & . & . & & . \\ 0 & 0 & 0 & \ldots & m_n \end{bmatrix}$$

$$[B] = \begin{bmatrix} -m_1 x_1 & -m_2 x_2 & -m_3 x_3 \ldots & -m_{n-1} x_{n-1} & -m_n x_n \\ +\sum_2^n mx & -m_2 x_2 & -m_3 x_3 \ldots & -m_{n-1} x_{n-1} & -m_n x_n \\ 0 & +\sum_3^n mx & -m_3 x_3 \ldots & -m_{n-1} x_{n-1} & -m_n x_n \\ . & . & . & & \\ . & . & . & & \\ . & . & . & & \\ 0 & 0 & 0 & \ldots -m_{n-1} x_{n-1} & -m_n x_n \\ 0 & 0 & 0 & \ldots +m_n\ x_n & -m_n x_n \end{bmatrix}$$

and $\sum_2^n mx = \sum_{j=2}^{n} m_j x_j$ etc.

Being a triangular matrix, A is comparatively easy to invert. Premultiply equation (4) by A^{-1} and obtain

$$\{F\} = [\omega^2 D + \Omega^2 A^{-1} B]\ \{y\} - \Omega^2 y_0 [A]^{-1} \{C\} \qquad (5)$$

so defining the equivalent transverse loads $\{F\}$ in terms of the unknown displacements $\{y\}$ and the unknown root station displacement y_0.

A further equation relating F and y can be obtained by writing down the "elastic equation" which involves the influence coefficients a_{ij}.

3. THE ELASTIC EQUATION

Equating the root station displacements y_0 and ϕ_0 to zero and applying to the beam a set of forces F_j, the resulting displacements are defined by the elastic equation

$$\bar{y}_i = \sum_{j=1}^{n} a_{ij} F_j,$$

or in matrix form

$$\{\bar{y}\} = [a]\ \{F\} \qquad . \quad . \quad . \quad (6)$$

where $[a] = \begin{bmatrix} a_{11} & a_{12} & a_{13} & . & . & . & a_{1n} \\ a_{21} & a_{22} & a_{23} & . & . & . & a_{2n} \\ a_{31} & a_{32} & a_{33} & . & . & . & a_{3n} \\ . & . & . & & & & . \\ . & . & . & & & & . \\ . & . & . & & & & . \\ . & . & . & & & & . \\ a_{n1} & a_{n2} & a_{n3} & . & . & . & a_{nn} \end{bmatrix}$

For non-zero values of y_0 and ϕ_0, $\bar{y}_i$ and y_i are related by the equation

$$y_i = \bar{y}_i + y_0 - (x_i - x_0)\,\phi_0$$

or

$$\bar{y}_i = y_i - y_0 + (x_i - x_0)\,\phi_0$$

or again as the matrix equation

$$\{\bar{y}\} = \{y\} - y_0\{1\} + \bar{x}\phi_0 \left\{\frac{x - x_0}{\bar{x}}\right\}, \qquad (7)$$

where

$$\left\{\frac{x - x_0}{\bar{x}}\right\} = \left\{\frac{x_1 - x_0}{\bar{x}}\ \frac{x_2 - x_0}{\bar{x}}\ .\ .\ .\ .\ \frac{x_n - x_0}{\bar{x}}\right\}.$$

Substituting (7) into (6) gives

$$\{y\} = [a]\ \{F\} + y_0\{1\} - \bar{x}\phi_0 \left\{\frac{x - x_0}{\bar{x}}\right\} \quad . \quad (8)$$

Equations (5) and (8) can be combined to form a single matrix equation relating $\{y\}$ to the root displacements y_0 and ϕ_0. It remains to satisfy the boundary conditions at station 0.

4. BOUNDARY CONDITIONS AT STATION 0

To cover the most general case it will be assumed that rotation about station 0 is restrained by a spring of stiffness K_0. Due to the sign convention adopted in defining the beam bending moments and the root rotation, M_0 and ϕ_0 are related by the equation

$$M_0 = (M_i)_{i=0} = -K_0 \phi_0$$

From equation (1),

$$(M_i)_{i=0} = \sum_{j=1}^{n} \{\omega^2 m_j y_j (x_j - x_0) - \Omega^2 m_j x_j (y_j - y_0)\}.$$

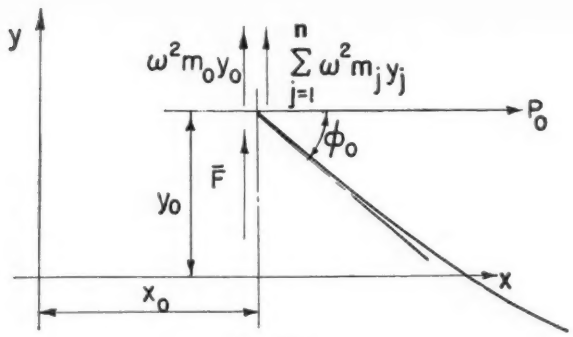

FIGURE 2.

Therefore

$$-K_0\phi_0 = \sum_{j=1}^{n} \{x_j m_j y_j(\omega^2 - \Omega^2) - \omega^2 x_0 m_j y_j + \Omega^2 y_0 m_j x_j\}$$

$$= \Omega^2 y_0 M\bar{x} - \omega^2 x_0 \sum_{j=1}^{n} m_j y_j + (\omega^2 - \Omega^2) \sum_{j=1}^{n} m_j x_j y_j \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

which forms one of the boundary conditions. A further equation is obtained by considering the vertical equilibrium of station 0. Let m_0 be the mass at this station

and $$P_0 = \Omega^2 \sum_{j=1}^{n} m_j x_j = \Omega^2 M\bar{x}$$

which is the centrifugal force at station 0.
For equilibrium,

$$\bar{F} + \omega^2 [m_0 y_0 + \sum_{j=1}^{n} m_j y_j] = 0 \quad . \quad . \quad (10)$$

5. SOLUTION OF THE EQUATIONS OF MOTION

The equations to be solved are

$$\{F\} = [\omega^2 D + \Omega^2 A^{-1} B]\{y\} - \Omega^2 y_0 [A]^{-1}\{C\} \quad (5)$$

$$\{y\} = [a]\{F\} + y_0\{1\} - \bar{x}\phi_0 \left\{\frac{x - x_0}{\bar{x}}\right\}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

the boundary conditions for the problem being

$$(\omega^2 - \Omega^2) \sum_{j=1}^{n} m_j x_j y_j - \omega^2 x_0 \sum_{j=1}^{n} m_j y_j = -K_0\phi_0 - \Omega^2 y_0 M\bar{x} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

$$\omega^2 \sum_{j=1}^{n} m_j y_j = -\omega^2 m_0 y_0 - F \quad . \quad . \quad (10)$$

A combination of equations (5) and (8) leads to a set of n linear simultaneous equations relating $y_1, y_2 \ldots y_n$ to y_0 and ϕ_0. It is apparent from the linear characteristics of the problem, that the solution of this set of equations must be of the form

$$y_i = \eta_j y_0 + \zeta_j \bar{x}\phi_0, \quad . \quad . \quad . \quad (11)$$

where η_j and ζ_j are both independent of the root displacements.

Equations (5) and (8) can now be separated into two sets of equations in η_j and ζ_j:—

$$\left.\begin{aligned} \left\{\frac{F_\eta}{y_0}\right\} &= [\omega^2 D + \Omega^2 A^{-1} B]\{\eta\} - \Omega^2 [A]^{-1}\{C\} \\ \{\eta\} &= [a]\left\{\frac{F_\eta}{y_0}\right\} + \{1\} \end{aligned}\right\} . \quad (12)$$

$$\left.\begin{aligned} \left\{\frac{F_\zeta}{\bar{x}\phi_0}\right\} &= [\omega^2 D + \Omega^2 A^{-1} B]\{\zeta\} \\ \{\zeta\} &= [a]\left\{\frac{F_\zeta}{\bar{x}\phi_0}\right\} - \left\{\frac{x - x_0}{\bar{x}}\right\} \end{aligned}\right\} . \quad . \quad . \quad (13)$$

The boundary conditions (9) and (10) can also be written in terms of η_j and ζ_j. Equation (9) then becomes an equation for $\bar{x}\phi_0/y_0$:—

$$\frac{\bar{x}\phi_0}{y_0} = -\left[\frac{\Omega^2 M\bar{x} - \omega^2 x_0 \sum_{j=1}^{n} m_j\eta_j + (\omega^2 - \Omega^2) \sum_{j=1}^{n} m_j x_j \eta_j}{\frac{K_0}{\bar{x}} - \omega^2 x_0 \sum_{j=1}^{n} m_j\zeta_j + (\omega^2 - \Omega^2) \sum_{j=1}^{n} m_j x_j \zeta_j}\right] \quad (14)$$

Equation (10) becomes

$$\frac{\bar{F}}{y_0} = -\frac{\bar{x}\phi_0}{y_0} \cdot \omega^2 \sum_{j=1}^{n} m_j\zeta_j - \omega^2 [m_0 + \sum_{j=1}^{n} m_j\eta_j]. \quad (15)$$

$\bar{F}/y_0$ is the impedance of the system which vanishes when ω is one of the natural frequencies.

The procedure can be summarised as follows:—

(*i*) Solve equations (12) and (13) for the known values of Ω and for a range of assumed values of ω.

(*ii*) Substitute the values of η and ζ into equation (14) and calculate the corresponding range of values of $\bar{x}\phi_0/y_0$.

(*iii*) Calculate the impedance of the system from equation (15) and plot $\bar{F}/y_0$ against ω.

(*iv*) If necessary, check the natural frequencies so found by repeating (*i*), (*ii*) and (*iii*) at the values of ω at which $\bar{F}/y_0$ vanishes.

The mode shape can be found from equation (11):—

$$\frac{y_j}{y_0} = \eta_j + \frac{\bar{x}\phi_0}{y_0}\zeta_j.$$

The most usual case met in practice is that of the helicopter rotor blade which is freely articulated at station 0. For this case $K_0 = 0$, thus slightly modifying equation (14).

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The author is indebted to Mr. Raoul Hafner, Chief Designer (Helicopters) of the Bristol Aeroplane Company for permission to publish this note.

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2. HORVAY, G. (1948). Chordwise and Beamwise Bending Frequencies of Hinged Rotor Blades. *Journal of the Aeronautical Sciences*, Volume 15, August 1948.
3. HIRSCH, H. The Contribution of Higher Mode Resonance to Helicopter Rotor Blade Bending (Fig. 5). (C.A.L. Report).

THE LIBRARY
Reviews

COMPONENT DESIGN. HANDBOOK OF AERONAUTICS No. 2. *Published under the authority of the Council of the Royal Aeronautical Society. Pitman, London, 1954. 207 pp. Diagrams. 30s.*

Even in 1931, when the first Handbook was published, to cover in one volume the highly complex subject of aeronautical engineering was an ambitious undertaking. Since then, quite apart from a widening of the general basis, many additional branches of engineering have been included. This situation has been recognised, and the latest edition is being published in several volumes, of which "Component Design" is the second. Others deal with structural principles, aerodynamics, performance, power plants and materials.

Component Design should prove most useful to the airframe designer/draughtsman, particularly the project man. In addition to structures it covers, in some detail, a number of specialist subjects such as undercarriages and air conditioning. While these may not be comprehensive enough for the specialist (apart from providing a good introduction), they are of real value to the man who is interested in their effect on basic airframe layout and design.

Students will find in the book a useful introduction to both airframe design and specialist installations.

The work, which is adequately illustrated throughout, is divided into sections, each by a different author.

Aircraft Structures—M. Langley

The principles of wing and fuselage structures are discussed, somewhat briefly, but many examples are described in detail and excellently illustrated. Some of the "do's" and "don'ts" might, with advantage, have been given, particularly those affecting weight saving, fatigue resistance, etc., but perhaps they will be covered in another volume.

The Landing Gear—H. G. Conway.

It might be argued that too much space has been given to this section when compared with, say, aircraft structures; however, it covers the whole subject in a competent manner. Undercarriage layout, principles of shock absorber design, stressing, retraction and brakes are among the many aspects discussed.

Riveting—M. Langley.

Riveting is dealt with in some detail, including the design of riveted joints, workshop practice and descriptions of the many forms of riveting now available.

Air Conditioning—J. R. Leach.

Relatively new among aeronautical engineering problems, air conditioning and pressurisation have become a major item. J. R. Leach has managed to condense into some 23 pages most of the important considerations ranging from physiological aspects and basic requirements to sealing and insulating the cabin.

Control Systems—A. Symon.

This is a short section which, while dealing adequately with the various forms of manual control system, makes a somewhat sketchy reference to the more recent problems of power controls.

Power Actuating Systems—H. G. Conway.

The ramifications of power actuation on modern aircraft have become so widespread that the subject really justifies a separate volume written by hydraulic, pneumatic and electrical specialists. The present author tends to make his preference a little too obvious. However, the relative merits of various systems are discussed and good examples of each are described in some detail. Operating requirements are stated and some useful information is given on the design of hydraulic jacks.

Fuel Systems—J. G. H. Cooper.

This section covers most of the basic requirements for fuel systems including tank design, pipe installations, etc., together with descriptions of various fuel system accessories such as valves, cocks, gauging systems, filters, recuperators.

Weight Estimation and Control—R. S. Austin.

The importance of initial estimation and subsequent control of weight during the design of an aircraft has been widely recognised, particularly during the past 10 years or so. This section, which is largely devoted to weight estimation in the early stages of design, provides a lot of useful data for the project designer as well as the weight control engineer.—C. F. JOY.

AXIALKOMPRESSOREN UND RADIALKOMPRESSOREN. *B. Eckert. Springer, Berlin. 441 pp. Illustrated. D.M.73.50 (125s. approx.) (In German.)*

This is a book very definitely for the expert and is an impressive assembly of test data and design information.

It begins with three small chapters, the first describing the various types of compressor applications, the second introducing the various non-dimensional factors governing the performance of compressors, and the third the dynamics and thermodynamics required. These three chapters occupy 89 pages out of a total of 439, and how refreshing to find that the author does not assume the reader will never have heard of the gas laws so that a whole chapter must be devoted to them. In the reviewer's opinion exactly the correct balance is struck here between the fundamental background and the detailed information on the real subject in question.

The main section of the book follows in two large chapters, the first dealing with Axial and the second with Radial Compressors. These are followed by two small chapters, the first on unstable conditions of operation and the second on methods of regulation and control.

The section on axial compressors will be studied with great interest. A large number of tests on single stages are shown to illustrate the effects of variation of design parameters, information difficult to find elsewhere. Indeed it might be a possible criticism that the design methods are based too much on such data and not enough on performance derived from complete compressors. The design methods are extremely interesting, following the usual Continental practice derived from hydraulic theory, of the specific speed, which has found little or no use in axial compressor design here. The results of comparison of compressors designed by these rules come out very different from present designs of aero-compressors used here, generally the author is recommending designs of lower speed, larger sizes and much higher loading. In general it is disappointing to find that our designs seem to lie outside his field of reference completely. There is a large amount of test data on Reynolds number and the subject of three-dimensional flow is well treated. There is a large section on cascades of blades which follows the usual German method of calculation by transformation and correction of single aerofoil results rather than the

experimental cascade investigation method used here. With the wealth of test data available here the German method is usually considered unnecessary.

In the chapter on Radial Compressors, as with Axial Compressors, the author deals separately with compressors for industrial use and those of high loading capacity suitable for aircraft and gas turbines. Roughly, this separates compressors with bent back impeller vanes and no rotating guide vanes, and those with radial vanes and bent rotating guide vanes. Comparison of design data in this case with aero practice seems to give reasonable agreement. In both chapters the wealth of detail given and the design methods are extremely impressive, and make it, were it not for its price, a very desirable reference volume for the designer of compressors.

The small chapter on Unstable Operation is frankly disappointing and the author has not really made an attempt to cover this subject adequately.

This is indeed a worthy volume, but some adverse comments should be made. There are no doubt many ways of designing compressors but the problem that besets most of us from time to time is how to put them aright when they do not come up to expectation, particularly as regards premature surging. This book will not help people in this difficulty except in so far as to suggest how to design a different one. A chapter on the analysis of performance, derivation of stage characteristics, stage matching, and so on, would have been a helpful addition.

Secondly, there are no adequate lists of symbols and one has to search back page by page for identification. It would have been impractical to have a complete list for both types of compressor, but a separate one for each chapter is definitely desirable. Thirdly, surely in such an expensive book each new chapter could have begun on a separate page.—H. PEARSON.

PIONEER OF THE AIR: THE LIFE AND TIMES OF COLONEL S. F. CODY. *G. A. Broomfield. Gale & Polden, Aldershot, 1953. 64 pp. Illustrated. 10s. 6d.*

It was high time someone wrote a book about this admirable man, and now we have it we can be thankful it is a good and delightful book, and written by one who knew him and worked with him. Cody—not to be confused with Buffalo Bill Cody who was nevertheless his friend—had as romantic a career as any reader of the cartoon strips could imagine. American cowboy, crack-shot and buffalo killer, Klondike gold digger, Indian fighter, horse-dealer, showman, playwright, actor, kite-flyer and aeroplane pioneer, Cody first learnt of the air from the Chinese cook in his boyhood outfit who taught him to fly kites. He progressed by way of man-lifting kites, gliders (in 1905), to powered man-carrying aeroplanes.

Here we must say, with fervour, that if only Cody had been naturalised in 1908, instead of 1910, all the bitter nonsense now talked about certain claims to be the first Englishman to fly would have been knocked decisively on the head, for Cody unquestionably made the first proper powered aeroplane flights in this country—powered, sustained and controlled—on 16th May 1908, in his "British Army Aeroplane No. 1." He made five flights that day over Laffans Plain, the longest being 150 feet at a height of about 10 feet. On 5th October that year he flew 496 *yards*, at about 50 to 60 feet above ground.

He went on to make a number of machines and achieved notable successes, particularly by winning the British Military Trials Competition in 1912. He was killed with his passenger—Hampshire cricketer W. H. B. Evans—in a somewhat mysterious crash at Ball Hill near Cove Common in 1913, after a valuable and colourful career.

Although he derived his machines from the Wrights and Chanute—and his famous between-wing ailerons from Curtiss—he added ideas of his own based on his kiting experience, and was a fine and rugged pioneer when such men were badly needed to get aviation going. Many men alive today will remember his handsome figure on his magnificent white horse at Farnborough, or his white flying overalls topped by the famous ribbed crash helmet, nor will the "old-timers" forget his charming wife who had complete faith in her husband and his work, and was never afraid to go up with him.—C. H. GIBBS-SMITH.

VICTORY ON WINGS—WILBUR AND ORVILLE WRIGHT TAUGHT US HOW TO FLY. (*Overwinning op vleugels—Wilbur en Orville Wright leerden ons vliegen.*) *Henri Hegener. Drukkery De Spaarnestad, Haarlem, Holland, 1953. 16 pp. Illustrated. (In Dutch.)*

Hegener is one of the oldest Dutch aviation journalists with publications dating back to 1912. In his writing he has generally aimed at stimulating airmindedness and his best work has been in the field of the history of aviation.

The title of this book, which is written in Dutch, could be translated as: "Victory on Wings (Winged Victory)—Wilbur and Orville Wright taught us how to fly."

The book is well written and although the first few chapters give the impression of the story progressing rather slowly, this improves farther on and one reads the remaining chapters at a stretch.

It is almost a novel; the characters are well drawn, not as heroes or legendary supermen, but with full appreciation of their human qualities and shortcomings. The whole Wright family, including the brothers, proved to be people of fine character who lived up to their convictions.

The author knows the history of aviation thoroughly and his historical features are reliable and to the point.

The relations of the Wright brothers with the various people they met during their struggling years are described well and Chanute in particular has been clearly pictured.

The book is not a technical one; and was not intended to be; the technical explanations which the author gives at some points are not the strongest part of the book (*e.g.* page 132). It is a pity that the research done by the Wrights has been mentioned so modestly. Dr. Lewis, in his 1939 Wilbur Wright Memorial Lecture (*Journal of the Royal Aeronautical Society*, October 1939), made it clear that their research was one of the principal keystones of the ultimate success of the Wrights.

Written impartially and humanly, the book is well worth reading; Hegener has proved convincingly (if that be necessary) that the Wrights, although by no means the only ones who tried to realise heavier-than-air powered flight, were the first to achieve it.—H. J. VAN DER MAAS.

X-RAY DIFFRACTION PATTERNS OF LEAD COMPOUNDS. *Published by The Shell Petroleum Company, Thornton Research Centre, for private circulation (1954). 81 pp. Illustrations.*

This book is mainly a systematic presentation of the X-ray diffraction patterns of lead compounds studied at Thornton Research Centre. The information was vitally required for investigating the mechanism of the anti-knock action of lead as a fuel additive, and for research directed towards decreasing the penalty, in the form of combustion chamber deposits, involved in its use. Also included is a short, illustrated description of the examination of compounds by X-ray diffraction techniques.

TRANSACTIONS OF THE SYMPOSIUM ON FLUID MECHANICS AND COMPUTING. *Interscience Publishers, New York, 1954. 243 pp. Diagrams. $5.*

With one exception, this volume contains all the papers read at the first symposium in applied mathematics, sponsored by the American Mathematical Society and the Office of Ordnance Research, U.S. Army, and held at New York University in April 1953. Unfortunately the discussions following the papers have not been printed.

The papers published are:—Mathematical Methods in Compressible Flow Theory by M. J. Lighthill; Boundary Layer Problems in Applied Mathematics by G. F. Carrier; Fourier Synthesis of Homogeneous Turbulence by Garrett Birkhoff; One-Dimensional Anisentropic Flows by G. S. S. Ludford and M. H. Martin; Approximate Methods for Computing Flow Fields by J. H. Giese; Results and Conjectures in the Mathematical Theory of Subsonic and Transonic Gas Flow by Lipman Bers; The Singular Solutions and the Cauchy Problem for Generalised Tricomi Equations by Alexander Weinstein; Remarks on the Theory of Partial Differential Equations of Mixed Type and Applications to the Study of Transonic Flow by P. Germain; Discussion on Transonic Flow by R. von Mises; Some Problems Solvable on Computing Machines by Mark Lotkin; Weak Solutions of Nonlinear Hyperbolic Equations and their Numerical Computation by Peter D. Lax; Computation of One-Dimensional Compressible Flows including Shocks by L. H. Thomas; The Deformation of a Thin Material Shell of Non-Uniform Thickness by a Detonation Wave by G. E. Hudson; Measurement of Spherical Shock Waves by Hubert Schardin.—E.C.P.

THE BOOK OF FLIGHT. *Kenneth M. King. Warne, London, 1954. 64 pp. Illustrated. 5s.*

This is an excellent book to give any boy from the age of nine onwards. All modern lads are interested in flight in either its factual or its fantastic (prophetic?) aspects and here he will find both. Jets, Rockets, Balloons, Gliders, Models, Rotating Wing, all are dealt with in interesting and simple language and there are enough illustrations to wean the type who is over-addicted to the prevalent "comic."—F.H.S.

ENERGY TRANSFER IN HOT GASES. *National Bureau of Standards, U.S. Department of Commerce, Washington, 1954. 126 pp. Illustrated. $1.50.*

This volume contains the Proceedings of a Symposium held in September 1951. From the viewpoint of the aeronautical engineer, the problems discussed invite interest in their application to prime movers of all kinds and to high-speed aerodynamics.

Sixteen papers were read by British and American scientists. Their titles are: Processes of Electronic Excitation in Relation to Flame Spectra, Studies of Some Polyatomic Flame Bands, Emission Spectra of Polyatomic Free Radicals, Distribution of OH Rotational Intensities in Flames, Spectroscopic Studies of Low-Pressure Combustion Flames, Studies of Emission and Absorption in Flames, Energy Distribution of CO Molecules in $CO-O_2$ Flames, High-Resolution Spectra of Hydrocarbon Flames in the Infrared, Infrared Spectra of Thermally Excited Gases, Present Position of the Theory of Flames, Detailed Mechanism of Elementary Reactions: Production of $OH(^2\Sigma+)$ in the H_2-O_2 Flame (Abstract only), Some Reactions of Atomic Hydrogen in Flames, Temperature of the Hydrogen-Fluorine Flame, Effect of Flame-Generated Turbulence on Heat Transfer from Combustion Gases, Astrophysicist's Concept of Temperature.—E.C.P.

AIRCRAFT ENGINES OF THE WORLD. *1954 Edition. Paul H. Wilkinson. 320 pp. Illustrated. Published by Paul H. Wilkinson, New York. Pitman's, London. 50s.*

This is a revised edition of the Eleventh Edition, published in 1953, of a well-known book. The information given in it, which includes complete descriptions of 15 new engines, is up to date as in May 1954. A new section has been added—on Accessories and Equipment.

JAHRBUCH DER LUFTFAHRT 1954. (*Year book of Air Transport*). *E. F. Reuss. Verlag Pohl & Co., Munich. 13s. 6d. (In German.)*

This pocket book gives detailed information on aeronautics in Germany. As might be expected the place of honour is taken by gliding. As for the rest, it mainly consists of scientific and administrative bodies. The latter are of course a skeleton of things to come, their size and scope being such that the things to come will look rather impressive.—J.S.

Additions to the Library

Boyd, R. L. F. and M. J. Seaton (*editors*). ROCKET EXPLORATION OF THE UPPER ATMOSPHERE. Pergamon. 1954.

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U.S. Dept. of Commerce. BIBLIOGRAPHY OF BOOKS AND PUBLISHED REPORTS ON GAS TURBINES, JET PROPULSION AND ROCKET POWER PLANTS. January 1950-December 1953. U.S.G.P.O. 1954.

Willis, A. H. THE TECHNICAL LECTURE. Quest Publications. 1953.

Reports

AERODYNAMICS

Boundary Layer

See also Thermo-aerodynamics and Testing and Instruments

Tabulation of the Blasius function with blowing and suction. H. W. Emmons and D. C. Leigh. A.R.C. Current Paper 157 (*5th June* 1953, *published* 1954).—(1.1.5).

The influence of surface waves on the stability of a laminar boundary layer with uniform suction. A.R.C. Current Paper No. 161 (*March* 1953, *published* 1954).

To estimate the destabilising effect of the waves likely to be encountered on wing surfaces which will be used with boundary layer suction, calculations have been made of the effect of small sinusoidal surface waves on the stability of the asymptotic suction profile. Curves are presented of the percentage increases in local suction flow v_s/U necessary to maintain the stability of the boundary layer at the same level as on a completely flat surface, for various values of the variables v_s/U, height: wavelength ratio and Reynolds number based on wavelength.—(1.1.2).

On calculating incompressible turbulent boundary layers with arbitrary pressure distribution. H. Schuh. KTH Aero TN 41 (1954).

The turbulent boundary layer can be characterised with sufficient accuracy by two quantities: The momentum thickness and a profile parameter. More recent papers show agreement between various authors on the method of calculating the momentum thickness, but for the profile parameter different methods have been put forward. For calculating the latter quantity an integral form of the boundary layer equation is used in the present paper in a form which allows the coefficients in this equation to be obtained directly from experiments.—(1.1.3).

Laminar boundary layer on cone in supersonic flow at large angle of attack. F. K. Moore. N.A.C.A. Report 1132 (1953).

The laminar boundary-layer flow about a cone at large angles of attack to a supersonic stream has been analysed in the plane of symmetry. At the bottom of the cone, velocity profiles were obtained showing the expected tendency of the boundary layer to become thinner on the under side of the cone as the angle of attack is increased. At the top of the cone, the analysis failed to yield unique solutions, except for small angle of attack.—(1.1.1.4).

An exploratory investigation of skin friction and transition on three bodies of revolution at a Mach number of 1·61. *J. H. Hilton and K. R. Czarnecki. N.A.C.A. Technical Note* 3193 (*June* 1954).

Results are given of an exploratory investigation of the effects of pressure gradient on skin friction and boundary-layer transition of three bodies of revolution at a Mach number of 1·61. The pressure gradients investigated were those obtained on an ogive-cylinder, a cone-cylinder, and a blunt-base (N.A.C.A. RM-10) parabolic body, all having a fineness ratio of 12·2. Tests were made at zero angle of attack and over a Reynolds number range based on body length, from about $2{\cdot}5\times10^6$ to 37×10^6.—(1.1.2.4).

Investigation of distributed surface roughness on a body of revolution at a Mach number of 1·61. *K. R. Czarnecki, R. B. Robinson and J. H. Hilton. N.A.C.A. Technical Note* 3230 (*June* 1954).

An investigation has been conducted in the Langley 4- by 4-foot supersonic pressure tunnel to study the effect of surface roughness on the skin friction and temperature-recovery factor of an ogive-cylinder body of revolution at a Mach number of 1·61. Tests of models having four different surface roughnesses were made at zero angle of attack through a Reynolds number range (based on body length) of $2{\cdot}5\times10^6$ to 37×10^6. The drag, base pressure, and surface temperatures were measured for conditions of natural and fixed transition.—(1.1.1).

On the three-dimensional instability of laminar boundary layers on concave walls. H Görtler. N.A.C.A. Technical Memorandum 1375 (*June* 1954).

A study is made of the stability of laminar boundary-layer profiles on slightly curved walls relative to small disturbances that result from vortices whose axes are parallel to the principal direction of flow. The result is an eigenvalue problem by which, for a given undisturbed flow at a prescribed wall, the amplification or decay is computed for each Reynolds number and each vortex thickness. For neutral disturbances (zero amplification) a critical Reynolds number is determined for each vortex distribution.—(1.1.2.1).

Compressible Flow

See also Wings and Aerofoils

An experimental investigation of the pressure distribution on five bodies of revolution at Mach numbers of 2·45 *and* 3·19. *G. B. Marson, R. E. Keates and W. Socha. Cranfield Report* 79 (*April* 1954).

Measurements have been made in the College of Aeronautics $2\frac{1}{2}$ in. × $2\frac{1}{2}$ in. intermittent high speed tunnel of the pressure distributions on five non-lifting bodies of revolution of different nose angles at zero incidence. The tests were made at Mach numbers of 2·45 and 3·19. The results are compared with the pressure distributions given by two approximate theoretical methods, and good agreement is found at the Mach numbers used.—(1.2.3).

Théorie des corps élancés. E. A. Eichelbrenner. O.N.E.R.A. Publication No. 68 (1954).—(1.2.3).

Method for rapid determination of pressure change for one-dimensional flow with heat transfer, friction, rotation, and area change. J. E. Hubbartt, H. O. Slone and V. L. Arne. N.A.C.A. Technical Note 3150 (*June* 1954).

An approximate method for rapid determination of the pressure change for subsonic flow of a compressible fluid under the simultaneous action of heat transfer, friction, rotation, and area change is developed. In the development of this method, the momentum equation was approximated and rearranged for a convenient solution employing charts.—(1.2.1).

Some new drag data on the N.A.C.A. RM.-10 missile and a correlation of the existing drag measurements at $M=1{\cdot}6$ *and* 3·0. *R. J. Carros and C. S. James. N.A.C.A. Technical Note* 3171 (*June* 1954).

Measurements of the zero-lift total drag of the N.A.C.A. RM-10 missile were made on gun-launched, free-flight models at Mach numbers of 1·6 and 3·0 and corresponding Reynolds numbers of 3·0 million and 5·0 million. Results showed transition location to have an important effect on the drag. Results of this and several other investigations were correlated on the basis of considerations of Mach number, Reynolds number, transition location, and heat-transfer effects.—(1.2.3).

Control Surfaces

Aerodynamic loads on a leading-edge flap and a leading-edge slat on the N.A.C.A. 64A010 airfoil section. J. A. Kelly and G. B. McCullough. N.A.C.A. Technical Note 3220 (*June* 1954).

Load data in the form of chordwise distributions of pressure, normal-force, chord-force, and moment-coefficients are presented for a leading-edge flap and leading-edge slat installed on a two-dimensional N.A.C.A. 64A010 aerofoil. Pressure data for various model arrangements are presented in tabular form. The data were obtained for a Reynolds number of 6 million.—(1.3.4 × 10.2.1).

NOTE:—*The figures in parentheses at the end of each Summary are for office use only.*

FLUID DYNAMICS

Variation of local liquid-water concentration about an ellipsoid of fineness ratio 5 moving in a droplet field. R. G. Dorsch and R. J. Brun. N.A.C.A. Technical Note 3153 (*July* 1954).

Analyses of calculated water-droplet trajectories show that the concentration of liquid water at various points about an ellipsoid of revolution moving through a droplet field varies considerably. Curves of local concentration factor as a function of spatial position are presented in terms of dimensionless parameters.—(1.4).

A new hodograph for free-streamline theory. A. Roshko. N.A.C.A. Technical Note 3168 (*July* 1954).

The Helmholtz-Kirchoff method for separated flow past a flat plate normal to the stream is modified to allow arbitrary separation velocity and base pressure so that values more in conformity with experiment may be chosen. The solution depends on a single base-pressure parameter k. The computations depend on a particular choice of free-streamline hodograph which gives a definite wake width for every value of k. In this way the wake width is correlated with the drag.—(1.4.1).

On the drag and shedding frequency of two-dimensional bluff bodies. A. Roshko. N.A.C.A. Technical Note 3169 (*July* 1954).

A semi-empirical study was made of the bluff-body problem. The relation between the wake and the potential flow outside the wake and cylinder was studied and some experiments were made with interference elements in the wake close behind a cylinder. Free-streamline theory was combined with experimental results to obtain a correlation between bluff cylinders of different shapes.—(1.4.0).

Study of the subsonic forces and moments on an inclined plate of infinite span. B. H. Wick. N.A.C.A. Technical Note 3221 (*June* 1954).

A study has been made of the flow about an inclined plate, the forces on the plate, the adequacy of theory in predicting the forces, and the extent to which the force characteristics of the plate are indicative of those of thin aerofoil sections. —(1.4.1 × 1.10.0).

STABILITY AND CONTROL

See also WINGS AND AEROFOILS

An analytical investigation of airplane spin-recovery motion by use of rotary-balance aerodynamic data. S. H. Scher. N.A.C.A. Technical Note 3188 (*June* 1954).

A method for analytically investigating the motions of an aeroplane while in a spin or a recovery from the spin by use of applicable equations of motion, modified wind-tunnel rotary-balance measurements, and spin-geometry relationships is presented and applied to the step-by-step calculation of the spin recovery for one aeroplane configuration.—(1.8.3).

THERMO-AERODYNAMICS

Measurement of heat transfer in the turbulent boundary layer on a flat plate in supersonic flow and comparison with skin-friction results. C. C. Pappas. N.A.C.A. Technical Note 3222 (*June* 1954).

Local heat-transfer rates and average skin-friction coefficients on the surface of a heated flat plate at zero incidence to the air stream at Mach numbers of 1·69 and 2·27 are presented for a Reynolds number range of 10^6 to 10^7. The variation of heat transfer with Mach number was found to be the same as that of directly measured skin friction on unheated bodies.—(1.9.1. × 1.1.3.4).

WINGS AND AEROFOILS

See also FLUID DYNAMICS

Changes in control characteristics with changes in flow pattern at high subsonic speeds. Test on an EC. 1250 *aerofoil with* 25 *per cent. concave control flap. Parts I and II. R. A. Shaw. R. & M.* 2436 (*April* 1949, *published* 1954).

This report describes results obtained in wind-tunnel tests where it was found that considerable changes in flow pattern and pressure distribution around an aerofoil with control flap occurred in certain conditions for a small increase in speed or change in incidence or control angle. The changes were found first between $M = 0{\cdot}85$ and $0{\cdot}87$, when the shock-stalled flow, which had developed at lower speeds, was replaced, on one surface only, by streamline, flow extending almost to the trailing edge.—(1.10.2.1).

Further experiments on an N.A.C.A. 23021 *aerofoil with a* 15 *per cent. Handley Page slotted flap in the compressed air tunnel. R. Jones and A. H. Bell. R. & M.* 2519 (*7th August* 1946, *published* 1954).

The N.A.C.A. 23021 aerofoil was tested with a form of flap and slot which was a modification of the form tested as described in R. & M. 2305. The main modification was a rounding-off of the trailing edge of the main wing on the lower surface and of the leading edge of the flap, thus making the gap on the lower surface appreciably larger.—(1.10.2.1).

Notes on the induced drag of a wing-tail combination. C. H. Naylor. R. & M. 2528 (*July* 1946, *published* 1954).

An expression has been derived for the factor to be applied to ideal induced drag to allow for wing-tail interference. This factor is primarily dependant on the wing-tail lift and span ratios. It is of the order of 1·1 for a normal aircraft when the tailplane carries 10 per cent. of the weight of the aircraft, and can reach unexpectedly large values at high speed. Charts, generalised curves, and sufficient information are included to permit rapid evaluation of the factor for any particular case.—(1.10.2.2 × 7).

*Exact solutions for transonic flow past cusped aerofoils. H. C. Levey. A.R.L. Australia. Report A.*87 (*March* 1954).

Exact solutions are obtained for the flow of a compressible fluid past a family of cusped aerofoils by the hodograph method. The solutions are valid for mixed subsonic and supersonic flow (with $M_\infty < 1$), and are given in the form of convergent Fourier series for the stream-function and position co-ordinates in terms of the velocity magnitude and inclination.—(1.10.1.2).

*Supersonic wind tunnel tests of eleven small aspect-ratio wings. J. G. Laberge. N.A.E. Laboratory Report LR-*97 (*March* 1954).

The lift, drag and pitching moment characteristics of eleven small aspect-ratio half-wing models mounted on a reflection plate were determined in the range of Mach numbers from 1·4 to 2·5 in the N.A.E. 10-inch supersonic tunnel. Eight of the models were of the cropped delta type while the remaining three had a cropped arrow plan form.—(1.10.2.2).

A theoretical investigation of the aerodynamics of wing-tail combinations performing time-dependent motions at supersonic speeds. J. C. Martin, Margaret S. Diederich and P. J. Bobbitt. N.A.C.A. Technical Note 3072 (*May* 1954).

A theoretical investigation is presented on the contribution of the horizontal tail to the lift and pitching moment due to angle of attack, a constant rate of pitch, and a constant vertical acceleration. Numerical values of the aerodynamic coefficients associated with these motions are presented for a number of wing-tail combinations. A method of treating unsteady aerodynamics based on an infinite series of stability derivatives of successively higher order is presented.—(1.10.1.0 × 1.8.2).

Tables for the computation of wave drag of arrow wings of arbitrary airfoil section. F. C. Grant and M. Cooper. N.A.C.A. Technical Note 3185 (*June* 1954).

Tables and computing instructions are presented for the rapid evaluation of the wave drag of delta wings and of arrow wings having a ratio of the tangent of the trailing-edge sweep angle to the tangent of the leading-edge sweep angle from $-1{\cdot}0$ to $0{\cdot}8$. The tables cover a range of both subsonic and supersonic leading edges.—(1.10.1.2 × 1.2.3).

Dynamic stability and control characteristics of a cascade-wing vertically rising airplane model in take-offs, landings and hovering flight. Marion O. McKinney, L. P. Tosti and E. E. Davenport. N.A.C.A. Technical Note 3198 (*June* 1954).

An investigation has been made to determine the stability and control characteristics of a cascade vertically rising aeroplane model in the take-off, landing, and hovering phases of flight. The model had four propellers with the shaft axes essentially parallel to the fuselage axis and distributed along the span so that the four wings, which were arranged in cascade relation to turn the slipstream downward approximately 90°, were completely immersed in the slipstream of the propellers.—(1.10.2.2).

TESTING AND INSTRUMENTS

Calibration of the R.A.E. No. 18 (9 *in.* × 9 *in.*) *Supersonic Wind Tunnel Part I. Preliminary investigations. W. T. Lord and D. Beastall. A.R.C. Current Paper* 162 (*September* 1953, *published* 1954).

A detailed account is given of the investigations performed in the R.A.E. No. 18 (9 in. × 9 in., continuous flow, variable density) Supersonic Wind Tunnel prior to an extensive calibration of the tunnel. The variables which have an important effect on the behaviour of the flow are discussed, and preliminary experiments to determine their significance are described. The results of the investigations serve to define the course of the complete calibration, and may provide a useful guide to future calibrations of similar supersonic tunnels. The calibration programme is outlined.—(1.12.1.3).

Calibration of the R.A.E. No. 18 (9 *in.* × 9 *in.*) *Supersonic Wind Tunnel. Part II. Tests at atmospheric stagnation pressure. W. T. Lord, G. K. Hunt, R. J. Pallant and J. Turner. A.R.C. Current Paper* 163 (*September* 1953, *published* 1954).

This report presents distributions of Mach number in the empty working section of the R.A.E. No. 18 (9 in. × 9 in.) Supersonic Wind Tunnel at nominal Mach numbers of 1·4, 1·5, 1·6, 1·8 and 1·9, for condensation-free flow at atmospheric stagnation pressure and at a stagnation temperature of 35°C.—(1.12.1.3).

Evaporation from the surface of a body in an airstream (with particular reference to the chemical method of indicating boundary-layer transition). P. R. Owen and A. O. Ormerod. R. & M. 2875 (*September* 1951, *published* 1954).

The problem of predicting the rate of transport of a gas from or into the surface of a two-dimensional body in an air stream is discussed. The principal object of the investigation is to provide a means of estimating the time required to obtain an experimental record of boundary-layer transition when a chemical technique is used. The methods evolved should, however, find an application to other forced diffusion phenomena.—(1.12.0 × 1.1.2).

Lag in airborne pressure measuring systems. B. G. Newman. N.A.E., Canada. Laboratory Report LR-100 (*April* 1954).

The lag in the tubing of a pressure measuring system is considered as the sum of acoustic lag and viscous lag. The latter is due to the pressure drop associated with the flow down the tubing and is usually the larger. It is discussed theoretically and, following a series of ground measurements, a semi-empirical formula for viscous lag is obtained.—(1.12.5).

An investigation of the use of rocket-powered models for gust-load studies with an application to a tailless swept-wing model at transonic speeds. A. James Vitale, H. Press and C. G. Shufflebarger. N.A.C.A. Technical Note 3161 (*June* 1954).

Flight tests in continuous rough air to transonic speeds have been made of a tailless 45° swept-back wing rocket model as part of a programme to investigate the feasibility of using existing rocket-model techniques for obtaining gust-loads information. The results of aeroplane flight surveys for determining a working basis for forecasting and selecting suitable test days are presented.—(1.12.2 × 1.6.3).

MATERIALS

Contribution à la technique du moulage de précision de maquettes économiques en mixtes polyesters. L. Lansac and G. Dixmier. O.N.E.R.A. Note Technique No. 20 (1954).—(21.3.3).

Time-temperature parameters and an application to rupture and creep of aluminum alloys. G. J. Heimerl. N.A.C.A. Technical Note 3195 (*June* 1954).

The application of time-temperature parameters to stress-strain, rupture, and creep data for metals and alloys is reviewed. Some comparisons are made of theoretical and experimental parameters. Predictions of long-time life from short-time data are shown to be possible.—(21.2.2).

Role of nickel dip in enameling of sheet steel. D. G. Moore, J. W. Pitts and W. N. Harrison. N.A.C.A. Technical Note 3207 (*June* 1954).

An investigation was made of the effects of the firing time and the weight of the nickel deposited from the nickel-dip solution on the adherence developed by a cobalt-free and a cobalt-bearing ground-coat enamel on both enamelling iron and a titanium-bearing low-carbon steel.—(21.4).

NAVIGATION

The type V pictorial computer with automatic chart selection Part I. Development and initial tests. L. E. Setzer and P. H. Leake. C.A.A. Technical Development Report No. 199 (*June* 1954).

This report describes the Type V pictorial computer and presents the results of early laboratory and flight tests. The results of more extensive tests and evaluation are presented in Part II. The Type V computer is an airborne display of omnibearing and distance navigation information and provides continuous aeroplane-position and heading indications, a mechanical chart selector, and an automatic receiver-tuning mechanism. The charts are printed in route sequence on a roll of 35-mm film and are projected on a ten-inch diameter, see-through-type screen.—(26).

The type V pictorial computer with automatic chart selection Part II. Technical and operational evaluation. R. E. McCormick and F. S. McKnight. C.A.A. Technical Development Report No. 243 (*June* 1954).

This report describes the tests on the Type V pictorial display. Laboratory tests revealed that errors in the display do not exceed ±0·6° in bearing or 0·53 of a nautical mile in distance. Errors in aircraft-heading information were not greater than 1·5°. Controlled flight tests showed a maximum display error in indicated position of the aircraft of 0·6 of a mile when a chart scaled to 1:250,000 was used.—(26).

Technical and operational evaluation of the type IV pictorial-display equipment. E. Blount, C. E. Dowling, H. Kay, R. E. McCormick and E. R. Sellers. C.A.A. Technical Development Report No. 242 (*June* 1954).

This report describes the technical and operational evaluation of the Type IV rotatable-panel pictorial display. Laboratory tests revealed maximum errors of −0·4° and +0·5° in bearing, and of 0·75 of a nautical mile in distance in the pictorial-display portion of this equipment. Errors in the course-line-computer unit produced maximum displacements of 2·0 miles from the proposed course.—(26).

A preliminary study of operational advantages of pictorial navigation displays. F. S. McKnight. C.A.A. Technical Development Report No. 241 (*June* 1954).

In the preparation of an evaluation programme for the Types III, IV and V pictorial computers, a study of possible applications of these navigation displays to operational problems was required. This is a preliminary study of operational advantages of pictorial navigation displays with particular emphasis on application to air-traffic-control problems.—(26).

PROPELLERS

Oscillating pressures near a static pusher propeller at tip Mach numbers up to 1·20 *with special reference to the effects of the presence of the wing. H. H. Hubbard and L. W. Lassiter. N.A.C.A. Technical Note* 3202 (*July* 1954).

Static tests were conducted for the measurement of free-space oscillating pressures near the propeller in the region where a wing might be located for the tip Mach number range of 0·50 to 1·20. Some measurements were also made near the tips in the region of the fuselage to extend the range of existing work from a tip Mach number to 1·00 to 1·20. Some comparisons with theory are given.—(29.1).

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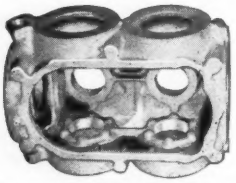

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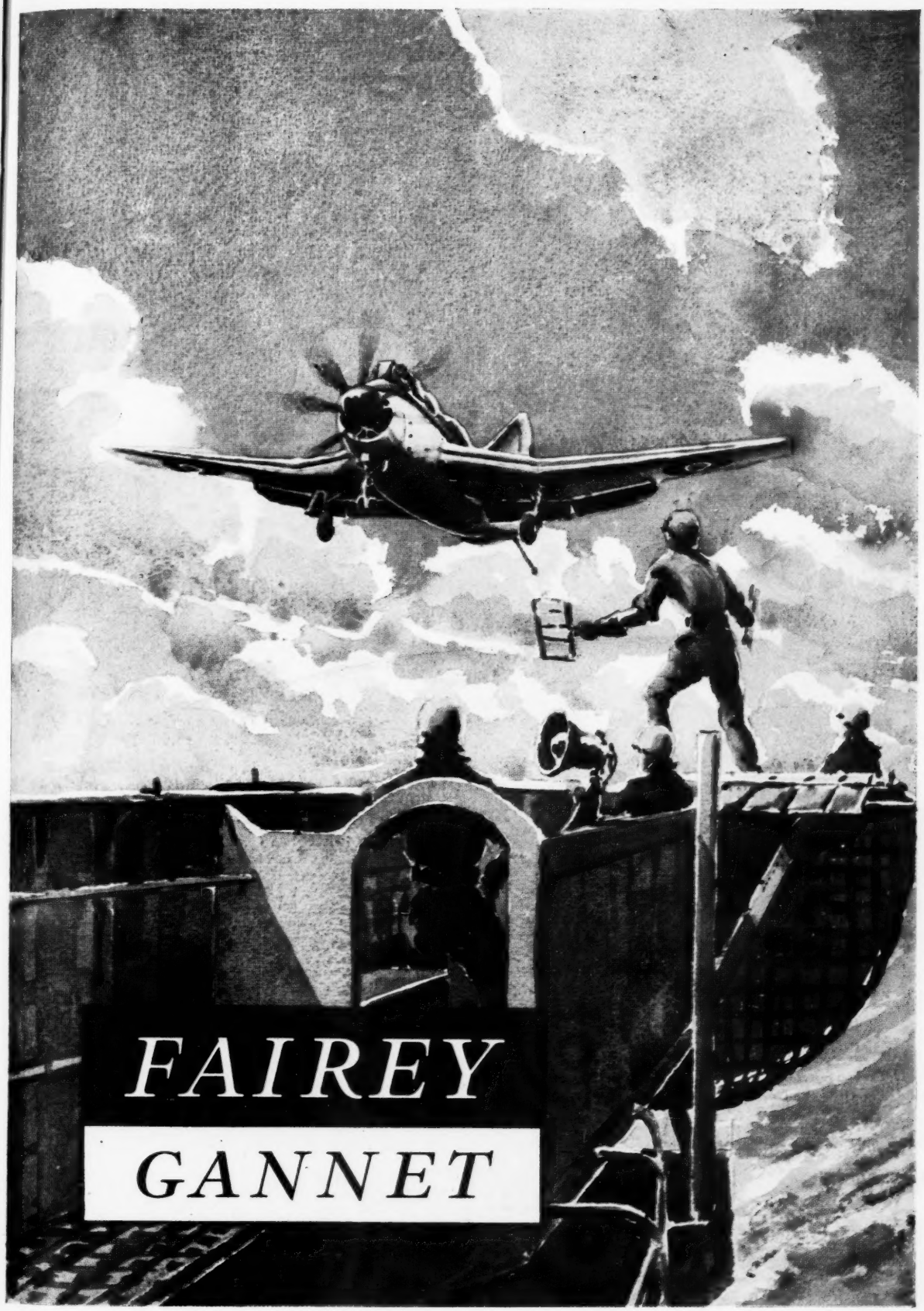

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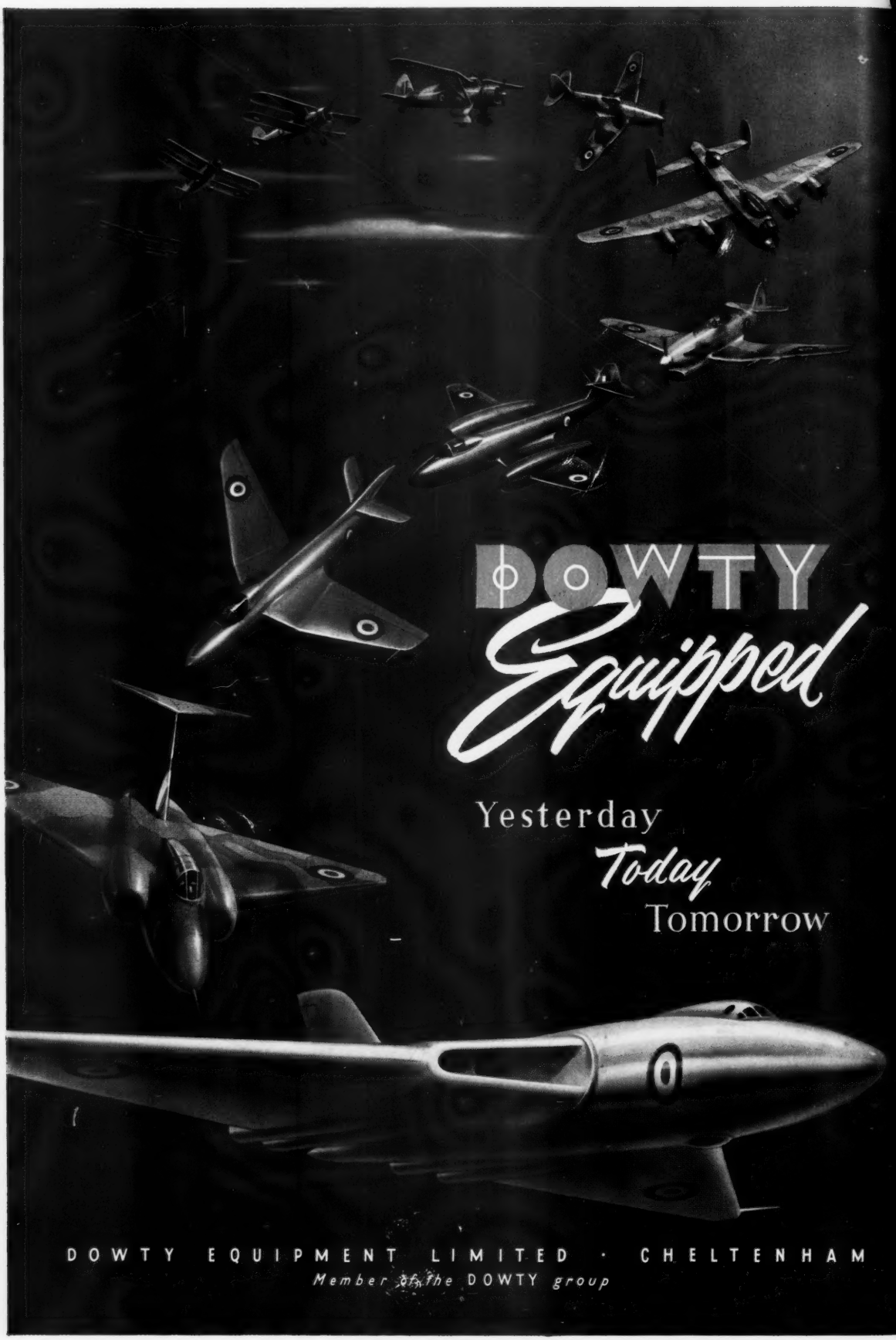

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